Summer 2021

JME 4110: Mass Production of Multi-Sphere Approximated Parts

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Joint Engineering Program

University of Missouri–St. Louis ▪ Washington University in St. Louis

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For this project, the team needs to design a mass production manufacturing process. The product of the process will be parts that represent, as closely as possible, approximations of parts developed using Discrete Element Modelling (DEM) software. Since the software uses spheres to efficiently model complex parts, the manufacturing process must also utilize spheres as the building blocks for the approximated parts. As a proof of concept, this project uses river pebbles as the parts being approximated by the software and modeled by the multi-sphere production process.

JME 4110
Mechanical Engineering
Design Project

Multi-Sphere Mass Production

Chris Hartley
Matthew Brady
Chad Gorski

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1 INTRODUCTION

1.1 VALUE PROPOSITION / PROJECT SUGGESTION

Imagine doing a computer simulation of the behavior of a bucket of something. If the parts don't behave as a fluid, you can model them as discrete elements using DEM (the Discrete Element Method). Turns out the easiest way for a computer to approximate a part shape is with a sphere. If you need more accuracy, you can model it as a bunch of spheres "smushed" together into a shape. Refer to the examples that will be shown in class. I need to manufacture a large number of these multi-sphere approximate models in actual material. Pick the material, obtain it in sphere form, decide if differing size spheres are allowed, design a method to "sinter" the spheres together into the desired arrangement. Ideally, the approximate parts can be un-sintered and broken apart and then sintered back together.

1.2 LIST OF TEAM MEMBERS

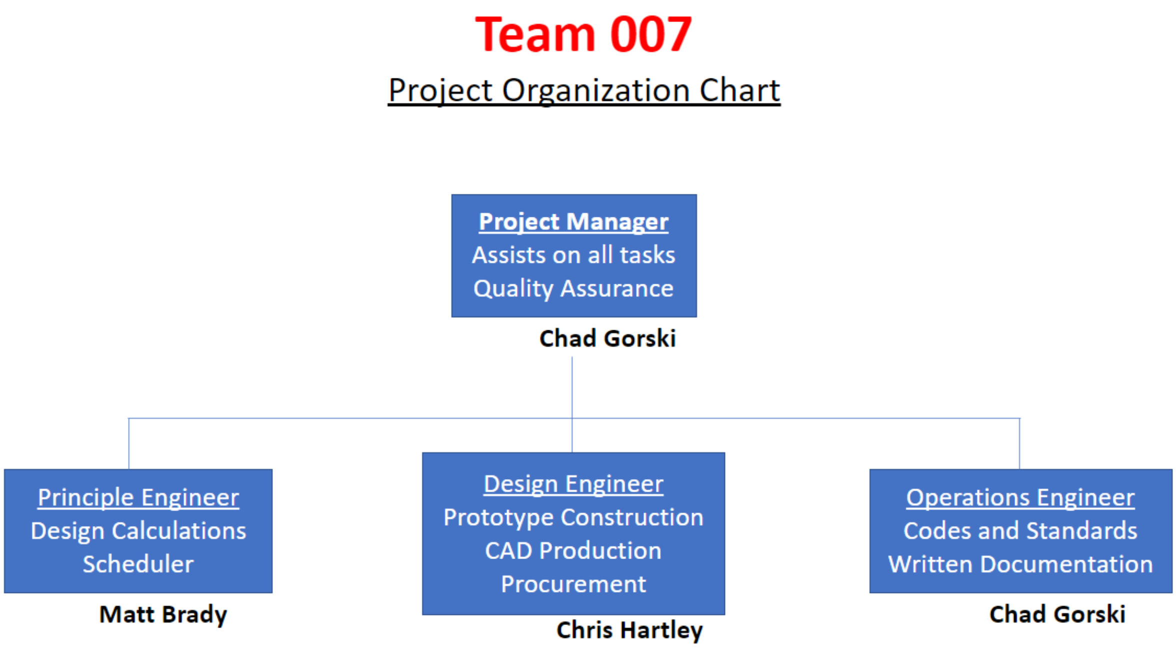


Figure 1: Project Organization Chart

2 BACKGROUND INFORMATION STUDY

2.1 DESGIN BRIEF

The scope of this project is to create a process to mass produce physical examples of computer approximations of parts. The parts are approximated using computer software to combine spheres of varying sizes such that they fit the approximate shape of the part while using the least possible number of spheres. Each sphere is then assigned specific material properties and treated like a discrete particle using the Discrete Element Method (DEM). The final use of these mass-produced multi-sphere approximate parts is to test the accuracy DEM software. The customer uses such software to model the interactions between small parts, such as seeds, when large quantities are handled simultaneously. There is currently no way to empirically prove that the software is using valid assumptions on which to base the predicted behaviors of the parts' motions and interactions.

As a means of validating and/or calibrating the software, the customer needs a process to mass produce multi-sphere parts that resemble the parts modeled in the software. The manufacturing process will involve "smushing" or deforming the spheres into each other to more closely resemble the desired parts. The spheres will range in size from 2 mm to 15 mm in diameter, and the final parts will be no larger than one cubic inch. The final parts will be rigid enough to withstand collisions with thousands of other parts during sifting and sorting processes.

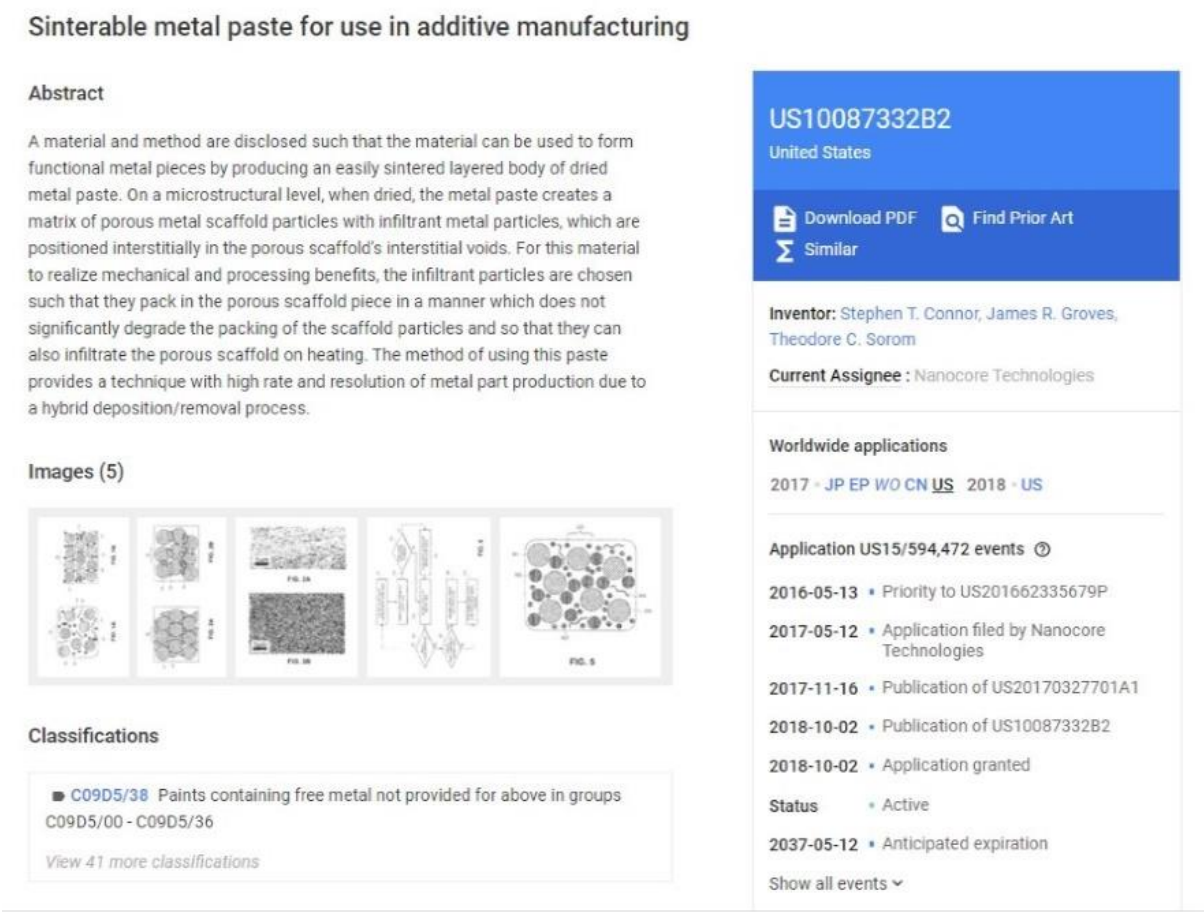
2.2 BACKGROUND SUMMARY

Similar Design (1):

Patent for Sinterable Metal Paste

Patent Number: US10087332B2

The metallic paste shown is figure 2 below is composed of eighteen (18) different metals. The porous metals form a scaffolding matrix, and infiltrant metals fill the interstitial voids, adding to the materials strength. This material melts when heated and solidifies on cooling, which is why it is suggested for additive manufacturing. Since this project is a form of additive manufacturing, this material may be a good representation of what the spheres could be made of. Alternatively, this paste can be used as a glue or epoxy to hold spheres of other materials in place.



Sinterable metal paste for use in additive manufacturing

Abstract

A material and method are disclosed such that the material can be used to form functional metal pieces by producing an easily sintered layered body of dried metal paste. On a microstructural level, when dried, the metal paste creates a matrix of porous metal scaffold particles with infiltrant metal particles, which are positioned interstitially in the porous scaffold's interstitial voids. For this material to realize mechanical and processing benefits, the infiltrant particles are chosen such that they pack in the porous scaffold piece in a manner which does not significantly degrade the packing of the scaffold particles and so that they can also infiltrate the porous scaffold on heating. The method of using this paste provides a technique with high rate and resolution of metal part production due to a hybrid deposition/removal process.

Images (5)

Classifications

C09D5/38 Paints containing free metal not provided for above in groups C09D5/00 - C09D5/36

View 41 more classifications

US10087332B2
United States

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Inventor: Stephen T. Connor, James R. Groves, Theodore C. Sorom

Current Assignee : Nanocore Technologies

Worldwide applications

2017 · JP EP WO CN US 2018 · US

Application US15/594,472 events

2016-05-13 • Priority to US201662335679P

2017-05-12 • Application filed by Nanocore Technologies

2017-11-16 • Publication of US20170327701A1

2018-10-02 • Publication of US10087332B2

2018-10-02 • Application granted

Status • Active

2037-05-12 • Anticipated expiration

Show all events

Figure 2: Patent for Sinterable Metal Paste from Google Patents [1]

Similar Design (2):

Spherical Magnets (Buckyballs)

Spherical magnets, similar to the ones shown in figure 2 below, are easy to form into countless patterns. With the help of some type of bonding agent (such as the metallic paste described above), the shapes formed by the magnets can be rigidly set into place. When the part is no longer needed, the bonding agent can be deactivated, and the magnets can be reused. The use of magnets does bring up questions about how multiple parts will interact with each other. If necessary, the magnets can be replaced with spheres of a different material and a mold can be used to help form the desired shape of the parts.

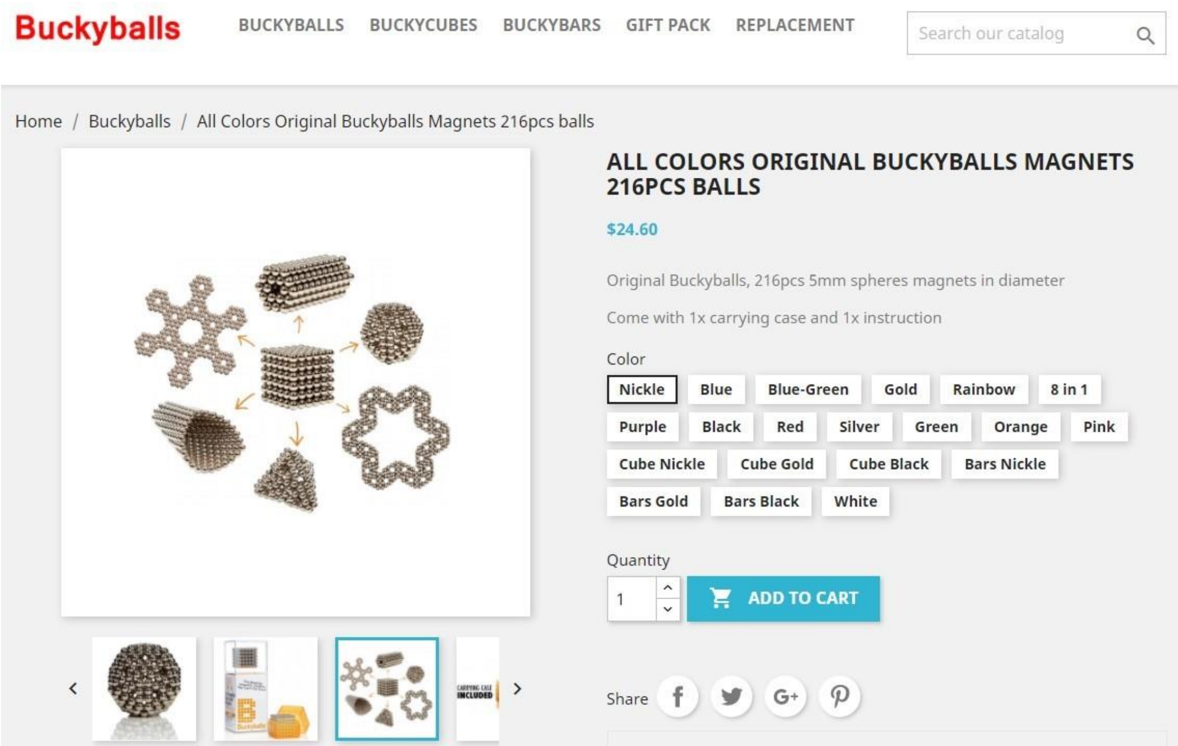


Figure 3: Buckyball Product Page [2]

3 CONCEPT DESIGN AND SPECIFICATION

3.1 USER NEEDS AND METRICS

3.1.1 Record of the user needs interview

Table 1: User Needs Interview Results

Project/Product Name: Multi-Sphere Part Mass Production (MSPMP)	
Customer:	**Interviewer(s):**
Mark Jakiela, JME-4110 Professor	Chris Hartley, JME-4110 student
	Chad Gorski, JME-4110 student
Address: Washington University	Matt Brady, JME-4110 student
Willing to do follow up? Yes	**Date:** 6/28/21
Type of user: Software Validation	Currently uses: None

Question	Customer Statement	Interpreted Need	Importance (0 to 5)
1) What are the bounding sizes for the spheres used in this process?	Min: 2mm Max: 15 mm	Min diameter = 2mm Max diameter = 15mm	2 3
2) After the parts are made and stored together, how are they allowed to interact with one another? (I.e., should they remain separated?)	As individual inert particles.	Parts do not stick together.	5
3) What features of an exact part should the approximate model most closely resemble?	Material Properties External shape	Similar in properties to 1" clean stone or river pebbles. Similar shape and volume to 1" clean stone or river pebbles.	4 4
4) What is the desired environment in which the production process can take place?	Standard, up-to-date machine shop	Follows codes and standards for large scale machining.	5
5) What is the maximum desired time per part/batch for the production process?	10 per minute	6 seconds per part	3
6) What type of environment/forces should the parts be made to withstand?	Forces from hitting other parts. (1000-part bin)	Can withstand a radial impact load up to 1,000 times its own weight.	4
7) What is the price range for materials and processing?	5 cents per part ($50 per 1000)	Cost < $50 per 1000 parts	3
8) What are some material characteristics of the parts that these "approximations" are modeling?	Smushing of spheres.	Spheres are malleable during construction. Parts (and spheres) are hard after construction.	1 4

Question	Customer Statement	Interpreted Need	Importance (0 to 5)
9) Who is the target customer? What is the end use of the approximated parts?	Dr. Jakiela (a software verification company)	Material behavior must be consistent.	5
10) What is the source for the DEM parts models being made?	Outside project scope	N/A	N/A
11) What is the required ratio (range) of spheres to bonding agent?	As little glue as necessary	Spheres are the primary component.	4

3.1.2 List of identified metrics

Table 2: Identified User Metrics

Need Number	Need	Importance
1	Spheres are less than 15 mm in diameter.	3
2	Spheres are greater than 2 mm in diameter.	2
3	MPMSA parts do not bond with mold/fixture at STP.	5
4	MPMSA parts have similar material and physical characteristics to 1" clean gravel.	4
5	MPMSA parts have a tetrahedron shape.	4
6	MPMSA parts have similar volume to that of a piece of 1" clean gravel.	4
7	MPMSA must follow codes and standards for a large-scale machine shop.	5
8	MPMSA must produce at least 10 parts per minute.	3

Need Number	Need	Importance
9	MPMSA parts have compressive strength greater than 1000 psi	4
10	MPMSA costs less than $0.05 per part for 1,000 parts.	3
11	MPMSA parts have consistent shape, size, and properties.	5
12	MPMSA parts composed of <5% bonding materials.	4

3.1.3 Table/list of quantified needs equations

Table 3: Quantified User Needs

Metric Number	Associated Needs	Metric	Units	Min Value	Max Value
1	1, 2	Sphere Diameter	mm	2	15
2	6	Volume of part	mm^3	50	7,000
3	4	Part density	kg/m^3	2,700	2,000
4	4, 9	Radial cracking (adhesion) force	lbf	1,000	1,500
5	5, 11	Comprised of 4 spheres	Boolean	0	1
6	7	Meets codes and standards	Boolean	0	1
7	8	Parts per minute	Integer	10	20
8	10	Cost per part	dollars	0.01	0.05
9	11	Shape variation	Percentage	1	10
10	11	Weight variation	Percentage	1	10
11	12	Percent bonding material	Percentage	0	5
12	3	Parts stick to mold	Boolean	0	1
13	4, 11	Young's modulus	GPa	35	57

3.2 CONCEPT DRAWINGS

Design 1: Porcelain Spheres Super Glued in a Triangular Wood Mold

Figure 4 below shows a process that uses 6 mm porcelain spheres that are used for tumbling. As described in the figure, triangular pockets engraved into a wooden base will be coated with precisely cut PTFE sheets to prevent the glue from bonding to the fixture. Three spheres will be placed in the fixture, dowsed with a moderate amount of Gorilla super glue, and topped with a fourth sphere using tweezers. Slight pressure applied briefly by hand to the top sphere should be sufficient to bond the tetrahedron together within 15 seconds. The parts can then be carefully removed with tweezers or a small pry bar and placed in a single layer on a separate sheet of PTFE until fully cured.

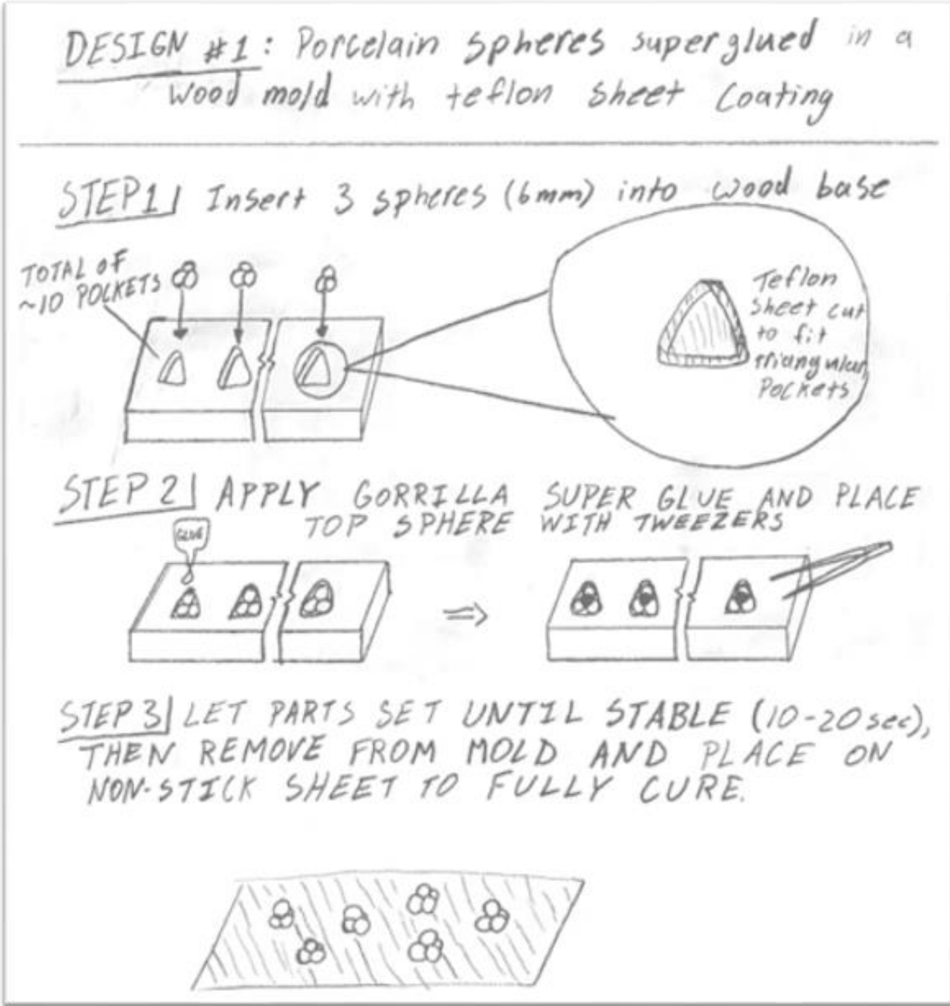


Figure 4: Proposed Design Using Porcelain Spheres and PTFE Sheets

Design 2: Agate Beads in Round Wooden Mold Using Spray Adhesive and Consumable Wax Paper

Figure 5 below depicts a second design that uses 10 mm agate beads as the sphere material, bonded together with Gorilla spray adhesive. The fixture for this design consists of the following main components:

1. Thin upper plate with through-drilled circles with a diameter roughly double the sphere diameter
2. Larger wooden base attached at the ends to the upper plate via two nails
3. A roll of wax paper fed between the upper plate and lower mount
4. A spill bucket to catch any overflow beads.

With the fixture mounted above the overflow bucket, beads are slowly poured into the circular holes in the upper plate. Once three spheres are in each circle, the base 3 spheres are sprayed with Gorilla spray adhesive before adding the final cylinder to each set individually. An additionally spray of adhesive is then applied to the tetrahedron. After allowing the adhesive to firm up, the wax paper is pulled through the slot between the wood pieces, forcing the parts to detach from the mold. The parts can then be place on a separate piece of wax paper to fully cure.

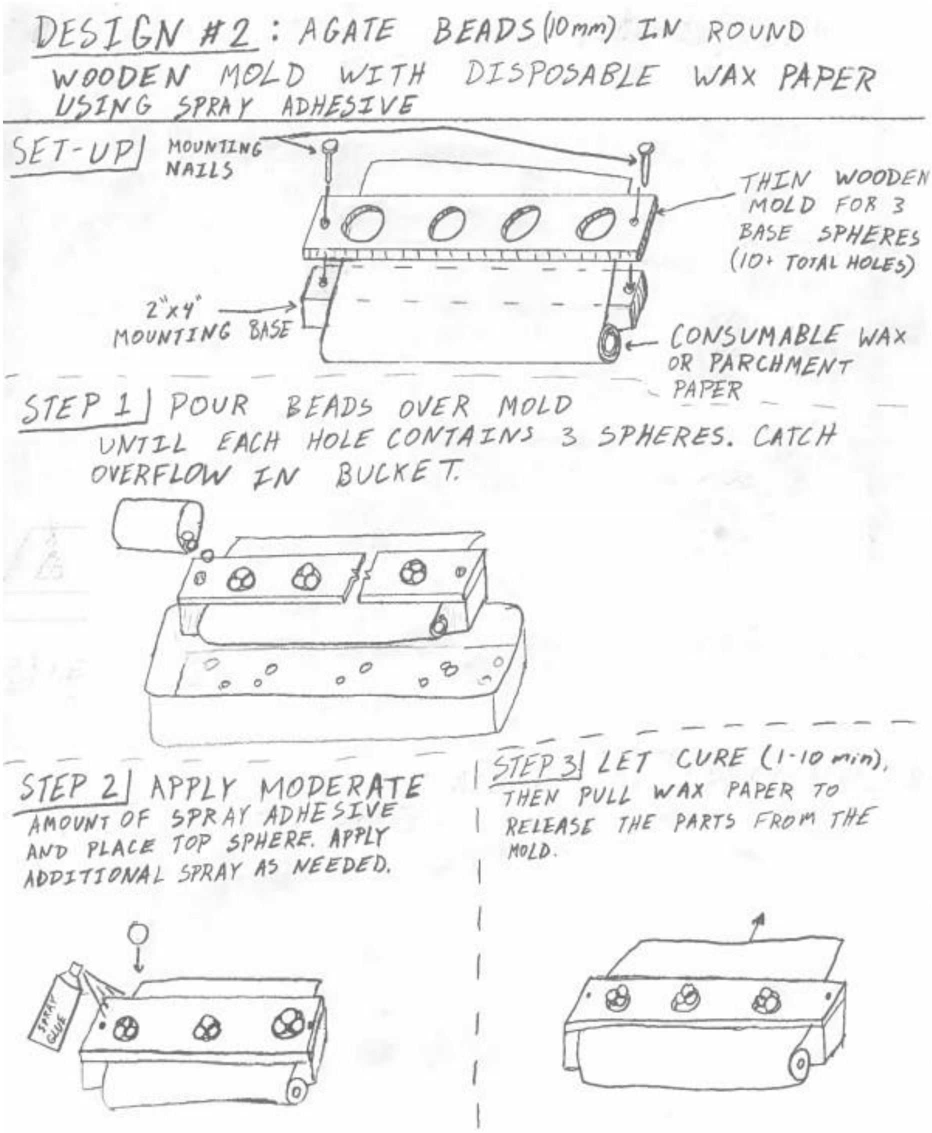


Figure 5: Agate Beads Bonded with Spray Adhesive Over Consumable Wax Paper

Design 3: Glass Spheres Epoxied in a Silicone Sphere Mold

Figure 6 below illustrates a design in which 10mm glass spheres are utilized as sphere material and are placed in a hopper for storage. The hopper rests over an HDPE locking plate meant to hold the spheres while the sphere tray is not in the assembly. With the locking plate removed, the spheres are free to settle into the sphere tray where a pre-cut silicone tray will receive the balls and gravity feed them into a tetrahedron configuration. The locking plate will be replaced and force balls not inside of a sphere tray tetrahedron back into the hopper, at which point the lower sphere tray can be removed and the 2-part adhesive can be placed on the spheres. This method of assembly can accommodate multiple sphere trays, should the need arise to have a higher rate of part construction while the other tray cures. If a sphere tray insert was to have an excessive number or inadequate number of spheres to form the tetrahedrons once the sphere tray is removed, the open top hopper design would allow for manual adjustment at any time.

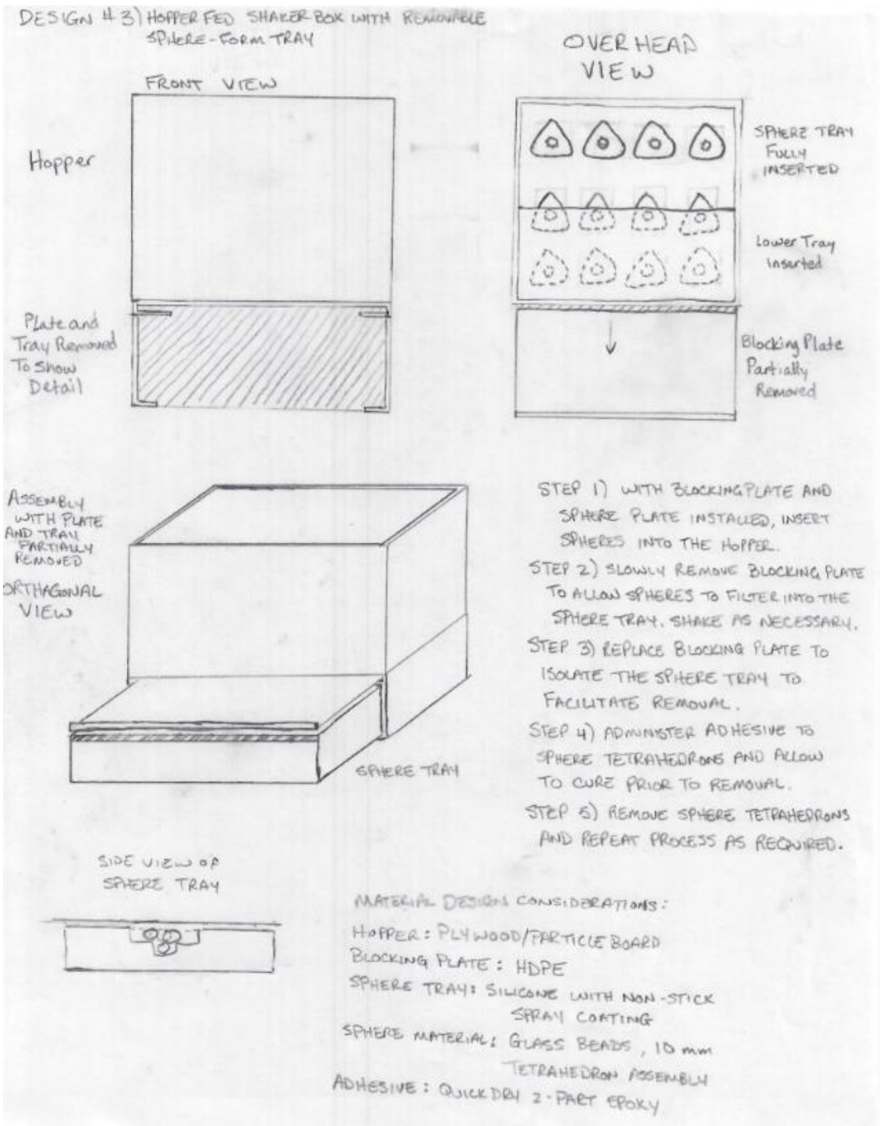


Figure 6: Proposed Design Utilizing Glass Spheres Epoxied in a Silicone Sphere Mold

Design 4: Garden Screen Mold with Steel Spheres and Spray Adhesive

Figure 7 below shows a design in which 8mm steel spheres are utilized with a simple frame and screen mold. The spheres are manually loaded into triangular configurations spaced over the metal screen material at which point the spray adhesive is applied to the first layer of spheres. Once this initial layer of adhesive is applied, a 4th sphere is applied on top of the base spheres and the assembly is sprayed a second time to solidify the entire tetrahedron.

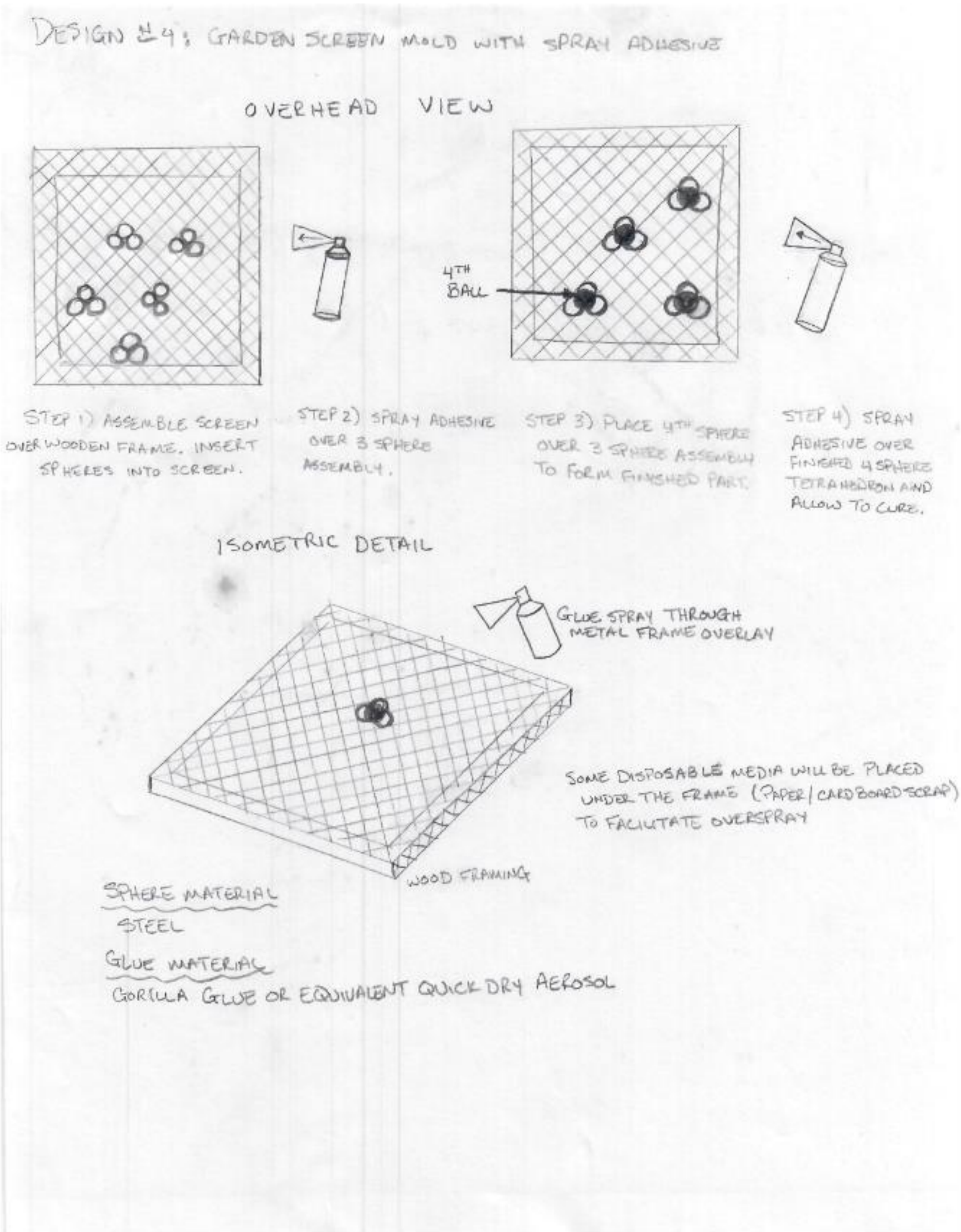


Figure 7: Proposed Design Utilizing Garden Screen with Steel Spheres and Spray Adhesive

3.3 A CONCEPT SELECTION PROCESS.

3.3.1 Concept scoring

Design 1: Super Glued Porcelain Spheres		Sphere diameter	Part Volume	Part density	Radial cracking force	Comprised of 4 spheres	Meets all codes and standards	Parts made per minute	Cost per part	Shape variation	Weight variation	Percent bonding material	Sticks to mold	Young's modulus	Need Happiness	Importance Weight (all entries should add up to 1)	Total Happiness Value
Need#	Need	1	2	3	4	5	6	7	8	9	10	11	12	13			
1	Sphere diam. <= 15 mm	1													0.692	0.065	0.045
2	Sphere diam. >= 2 mm	1													0.692	0.043	0.030
3	Parts do not bond to mold/fixture												1		1.000	0.110	0.110
4	Physically similar to 1" clean stone			0.33	0.33									0.33	0.614	0.087	0.053
5	Tetrahedron shape					0.5				0.5					0.972	0.087	0.085
6	Similar volume to 1" clean stone		1												0.942	0.085	0.080
7	Follows ???? Codes and Standards						1								1.000	0.110	0.110
8	Produce 10 parts per minute							1							0.500	0.065	0.033
9	Compressive strength greater than 1,000 psi				1										1.000	0.086	0.086
10	Costs less than $0.05 per part								1						0.500	0.065	0.033
11	Parts have consistent properties									0.5	0.5				0.972	0.110	0.107
12	Parts are primarily made up of spheres											1			0.600	0.087	0.052
Units		mm	mm^3	kg/m^3	lb	Boolean	Boolean	integer	$	%	%	%	Boolean	Gpa	Total Happiness		0.823
Best Value		2	50	2700	150	1	1	20	0.01	1	1	0	0	80			
Worst Value		15	7000	2000	100	0	0	10	0.05	10	10	5	1	35			
Actual Value		6	453	2400	150	1	1	15	0.03	1.5	1	2	0	48			
Normalized Metric Happiness		0.69	0.94	0.57	1.00	1.00	1.00	0.50	0.50	0.94	1.00	0.60	1.00	0.29			

Figure 8: Design 1 Super Glued Porcelain Spheres Happiness Derivation

Design 2: Agate Spheres in Circular Mold with Consumable Wax Paper		Sphere diameter	Part Volume	Part density	Radial cracking force	Comprised of 4 spheres	Meets all codes and standards	Parts made per minute	Cost per part	Shape variation	Weight variation	Percent bonding material	Sticks to mold	Young's modulus	Need Happiness	Importance Weight (all entries should add up to 1)	Total Happiness Value
Need#	Need	1	2	3	4	5	6	7	8	9	10	11	12	13			
1	Sphere diam. <= 15 mm	1													0.38	0.07	0.03
2	Sphere diam. >= 2 mm	1													0.38	0.04	0.02
3	Parts do not bond to mold/fixture												1		1.00	0.11	0.11
4	Physically similar to 1" clean stone			0.33	0.33									0.33	0.61	0.09	0.05
5	Tetrahedron shape					0.5				0.5					0.89	0.09	0.08
6	Similar volume to 1" clean stone		1												0.71	0.09	0.06
7	Follows **????** Codes and Standards						1								1.00	0.11	0.11
8	Produce 10 parts per minute							1							0.50	0.07	0.03
9	Compressive strength greater than 1,000 psi				1										0.00	0.09	0.00
10	Costs less than $0.05 per part								1						0.00	0.07	0.00
11	Parts have consistent properties									0.5	0.5				0.67	0.11	0.07
12	Parts are primarily made up of spheres											1			0.60	0.09	0.05
Units		mm	mm^3	kg/m^3	lb	Boolean	Boolean	integer	$	%	%	%	Boolean	Gpa	Total Happiness		0.6101673
Best Value		2	50	2700	150	1	1	20	0.01	1	1	0	0	80			
Worst Value		15	7000	2000	100	0	0	10	0.05	10	10	5	1	35			
Actual Value		10	2095	2630	25	1	1	15	0.84	3	5	2	0	78			
Normalized Metric Happiness		0.38	0.71	0.90	0.00	1.00	1.00	0.50	0.00	0.78	0.56	0.60	1.00	0.96			

Figure 9: Design 2 Agate Spheres in Circular Mold with Consumable Wax Paper Happiness Derivation

Design 3 - Hopper Fed Shaker Box with Removable Sphere Form Tray using 10mm Glass Beads		Sphere diameter	Part Volume	Part density	Radial cracking force	Comprised of 4 spheres	Meets all codes and standards	Parts made per minute	Cost per part	Shape variation	Weight variation	Percent bonding material	Sticks to mold	Young's modulus	Need Happiness	Importance Weight (all entries should add up to 1)	Total Happiness Value
Need#	Need	1	2	3	4	5	6	7	8	9	10	11	12	13			
1	Sphere diam. <= 15 mm	1													0.3846154	0.065	0.025
2	Sphere diam. >= 2 mm	1													0.3846154	0.043	0.0165385
3	Parts do not bond to mold/fixture												1		1	0.110	0.11
4	Physically similar to 1" clean stone			0.33	0.33									0.33	0.822381	0.087	0.0715471
5	Tetrahedron shape					0.5				0.5					1	0.087	0.087
6	Similar volume to 1" clean stone		1												0.7058417	0.085	0.0599965
7	Follows **????** Codes and Standards						1								1	0.110	0.11
8	Produce 10 parts per minute							1							0.2	0.065	0.013
9	Compressive strength greater than 1,000 psi				1										1	0.086	0.086
10	Costs less than $0.05 per part								1						0	0.065	0
11	Parts have consistent properties									0.5	0.5				0.7777778	0.110	0.0855556
12	Parts are primarily made up of spheres											1			0	0.087	0
Units		mm	mm^3	kg/m^3	lb	Boolean	Boolean	integer	$	%	%	%	Boolean	Gpa	Total Happiness		0.6646377
Best Value		2	50	2700	150	1	1	20	0.01	1	1	0	0	80			
Worst Value		15	7000	2000	100	0	0	10	0.05	10	10	5	1	35			
Actual Value		10	2094.4	2500	150	1	1	12	0.07	1	5	5	0	70			
Normalized Metric Happiness		0.384615	0.705842	0.714286	1	1	1	0.2	0	1	0.555556	0	1	0.777778			

Figure 10: Design 3 Hopper Fed Shaker Box with Removable Sphere Form Tray using 10mm Glass Beads Happiness Derivation

Design 4 - Garden Screen Mold with Spray Adhesive utilizing 8mm Steel Spheres		Sphere diameter	Part Volume	Part density	Radial cracking force	Comprised of 4 spheres	Meets all codes and standards	Parts made per minute	Cost per part	Shape variation	Weight variation	Percent bonding material	Sticks to mold	Young's modulus	Need Happiness	Importance Weight (all entries should add up to 1)	Total Happiness Value
Need#	Need	1	2	3	4	5	6	7	8	9	10	11	12	13			
1	Sphere diam. <= 15 mm	1													0.5384615	0.065	0.035
2	Sphere diam. >= 2 mm	1													0.5384615	0.043	0.0231538
3	Parts do not bond to mold/fixture												1		1	0.110	0.11
4	Physically similar to 1" clean stone			0.33	0.33									0.33	0	0.087	0
5	Tetrahedron shape					0.5				0.5					1	0.087	0.087
6	Similar volume to 1" clean stone		1												0.8529065	0.085	0.0724971
7	Follows ???? Codes and Standards						1								1	0.110	0.11
8	Produce 10 parts per minute							1							1	0.065	0.065
9	Compressive strength greater than 1,000 psi				1										0	0.086	0
10	Costs less than $0.05 per part								1						0	0.065	0
11	Parts have consistent properties									0.5	0.5				0.8888889	0.110	0.0977778
12	Parts are primarily made up of spheres											1			0.4	0.087	0.0348
Units		mm	mm^3	kg/m^3	lb	Boolean	Boolean	integer	$	%	%	%	Boolean	Gpa	Total Happiness		0.6352287
Best Value		2	50	2700	150	1	1	20	0.01	1	1	0	0	80			
Worst Value		15	7000	2000	100	0	0	10	0.05	10	10	5	1	35			
Actual Value		8	1072.3	8000	100	1	1	20	0.08	1	3	3	0	207			
Normalized Metric Happiness		0.538462	0.852906	0	0	1	1	1	0	1	0.777778	0.4	1	0			

Figure 11: Design 4 Garden Screen Mold with Spray Adhesive utilizing 8mm Steel Spheres Happiness Derivation

3.3.2 Preliminary analysis of each concept's physical feasibility

Design 1: Porcelain Spheres Super Glued in a Triangular Wood Mold

The main benefits of this design are cost and speed. The porcelain spheres can be purchased for less than \$0.01 each when bought in bulk, and only 1 to 2 drops of glue is used per tetrahedron. This brings the overall cost to about \$0.04 per part. The cure time of 10 seconds also keeps the production time relatively low.

Although the glue has a rapid dry time, this design lacks any automation, driving the assembly time of the parts up significantly. Also, even though super glue should not stick to PTFE in theory, this design does not have a clear method of attaching the PTFE sheets to the wood base. This introduces two prominent risks:

1. Gaps between separate pieces of PTFE sheets could allow glue to seep through, potentially binding the part to the wood base.
2. The PTFE sheet could easily slide out of the mold, increasing production time.

The overall "happiness" score for this design is **0.823.**

Design 2: Agate Beads in Round Wooden Mold Using Spray Adhesive and Consumable Wax Paper

This design is faster than the previous design because the spheres do not need to be placed individually in the mold, and the circular holes are more accepting when spheres are poured over them than triangular holes. The way in which wax paper is used in this design also limits the risk of the parts sticking to the mold. Agate is also a good material for the spheres because it can be found in rivers in the Midwest, which is exactly what we are attempting to model.

The downside of this material is that it is not particularly cheap. Another flaw of this design is that, although spray adhesive is much quicker to apply, it does not bond very well to stone materials. Even with materials that it does bond to, this adhesive has a long cure time. It can take up to 48 hours to fully cure. The overall "happiness" score for this design is **0.61.**

Design 3: Glass Spheres Epoxied in a Silicone Sphere Mold

Advantages to this design include some automation in the gravity fed design into premade molds and part storage in the hopper for faster assembly. Parts for this design are also relatively inexpensive to construct and could be scaled up or down with ease depending on the sphere diameter used. Some potential disadvantages are that the cure time on the 2-part adhesive may require multiple molds to ensure that the part production schedule is not affected, and there would have to be a very good closeness of fit between each sub part to ensure balls do not get stuck in between the removable pieces or forced into the hopper causing damage over time or loss of product. The overall "happiness" score for this design is **0.66.**

<u>Design 4: Garden Screen Mold with Steel Spheres and Spray Adhesive</u>

Advantages of this design are that any overspray would be filtered through the screen and be able to fall off the spheres, keeping the volume of adhesive low and minimizing weight variations. In addition, the simple design would allow for a large number of assemblies to be completed quickly, depending on the size of the frame built. Some disadvantages could include the need for 2 sprays of adhesive creating inaccurate weights between assemblies as well as sourcing the steel spheres could become problematic should steel prices fluctuate in a volatile market, making the overall price per part become unrealistic. The overall "happiness" score for this design is **0.64.**

3.3.3 Final summary statement

<u>Final Design: Super Glued Porcelain Spheres from a Hopper with Consumable Wax Paper</u>

Our final design is a combination of designs 1, 2, and 3. The material properties and cost of porcelain spheres makes it an ideal material for use in this application. The hopper depicted in design 3 can be used in conjunction with the mold from design 2 to increase the assembly time of the parts. A second mold with smaller circles cut into it can be used to guide the upper spheres into place as they are poured once glue is applied to each set of base spheres. Although the application of super glue is significantly slower than the application of spray adhesive, it has a much faster cure time and forms a much stronger bond with ceramic materials.

3.4 PROPOSED PERFORMANCE MEASURES FOR THE DESIGN

The most important user need for any design is that the parts can be removed from whatever creates them. If they cannot be removed, the stuck parts must be scrapped and production halts until they can be removed. The final design achieves this by incorporating a layer of parchment paper below the parts. The parchment paper can be removed after each batch to prevent buildup of glue, reducing the chances that parts will become stuck.

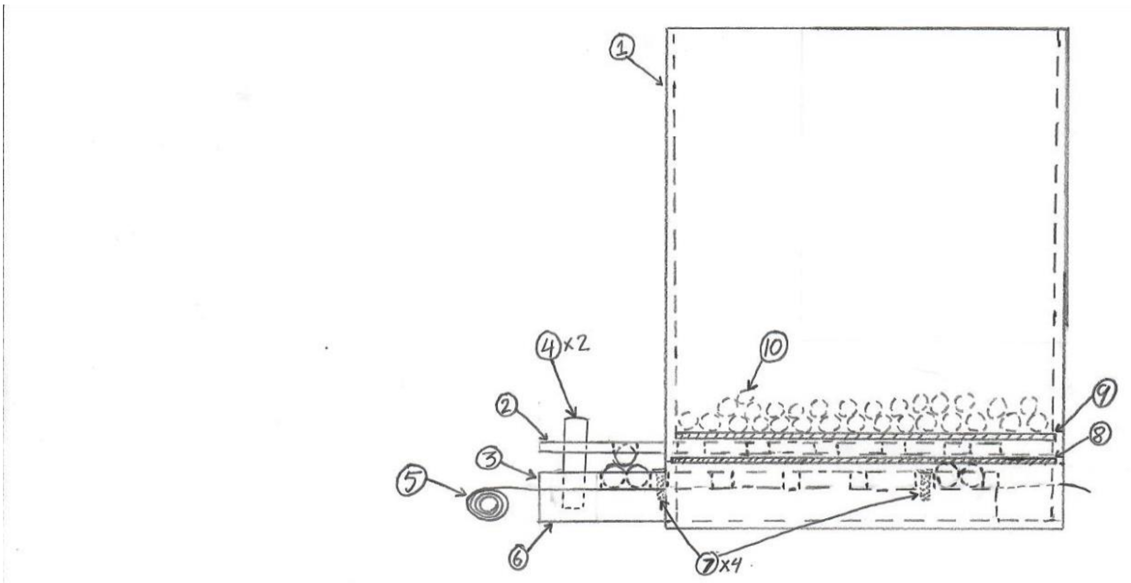
3.5 REVISION OF SPECIFICATIONS AFTER CONCEPT SELECTION

No revision of specifications was required after concept selection.

4 EMBODIMENT AND FABRICATION PLAN

4.1 EMBODIMENT/ASSEMBLY DRAWING

Figure 12 depicts a high level of the initial design concept for the production fixture. The “bill of materials” describes the necessary parts of the design.



BILL OF MATERIALS

ITEM NO.	DESCRIPTION	QUANTITY
1	HOPPER ENCLOSURE	1
2	UPPER MOLD	1
3	LOWER MOLD	1
4	ALIGNMENT PEGS	2
5	WAX PAPER ROLL	1
6	BASE PLATE	1
7	LOWER MOLD SET SCREWS	4
8	LOWER SEPARATOR PLATE	1
9	UPPER SEPARATOR PLATE	1
10	PORCELAIN SPHERES	4,000

Figure 12: Proposed Final Design Embodiment Drawing

4.2 PARTS LIST

Table 4: Proposed Final Design Part List

Item Number	Part Number	Description	Catalog Number	Unit Cost ($)	Web Link	Qty	Total Cost ($)
1	Base Plate	2x10 board cut to 8" long for Base Plate	NA	$9.84 [3]	bairdbrothers.com	1	$9.84
2	Plexiglass Sheet	24"x4"x0.22" Clear Acrylic Sheet for Hopper Walls	7453	$31.04 [4]	onlinemetals.com	1	$31.04
6	MDF Board	3/16"x24"x48" MDF Board for Upper and Lower Molds	313382855	$5.33 [5]	homedepot.com	1	$5.33
7	Porcelain Sphere	6mm Porcelain Spheres	293646027884	$25.22 [6]	ebay.com	1	$25.22
8	PTFE Plate	1/16"x12"x24" PTFE sheet for upper and lower separator plates	9266K22	$64.58 [7]	mcmaster.com	1	$64.58
10	Alignment Dowel Pin	1/4" dowel rod for alignment dowel pins	203360194	$1.07 [8]	homedepot.com	1	$1.07
11	Set Screw	1/4"-20x 1/2" set screws for clamping wax paper between lower mold and base plate	171684	$0.49 [9]	fastenal.com	4	$1.96
12	Parchment Paper	Non-stick parchment paper used to separate parts from lower mold and prevent sticking to base plate	8347585	$2.67 [10]	walmart.com	1	$2.67
13	Super Glue	Super glue used to bond spheres into final shape	7805001	$4.35 [11]	amazon.com	1	$4.35
					Total Cost:		$146.06

4.3 DRAFT DETAIL DRAWINGS FOR EACH MANUFACTURED PART

Figures 13 through 26 below show the detail drawings for each part in the original design of the production fixture. This design required that all spheres were always held inside the hopper and separator plates would allow them to fall into the molds at the proper stage of the production process.

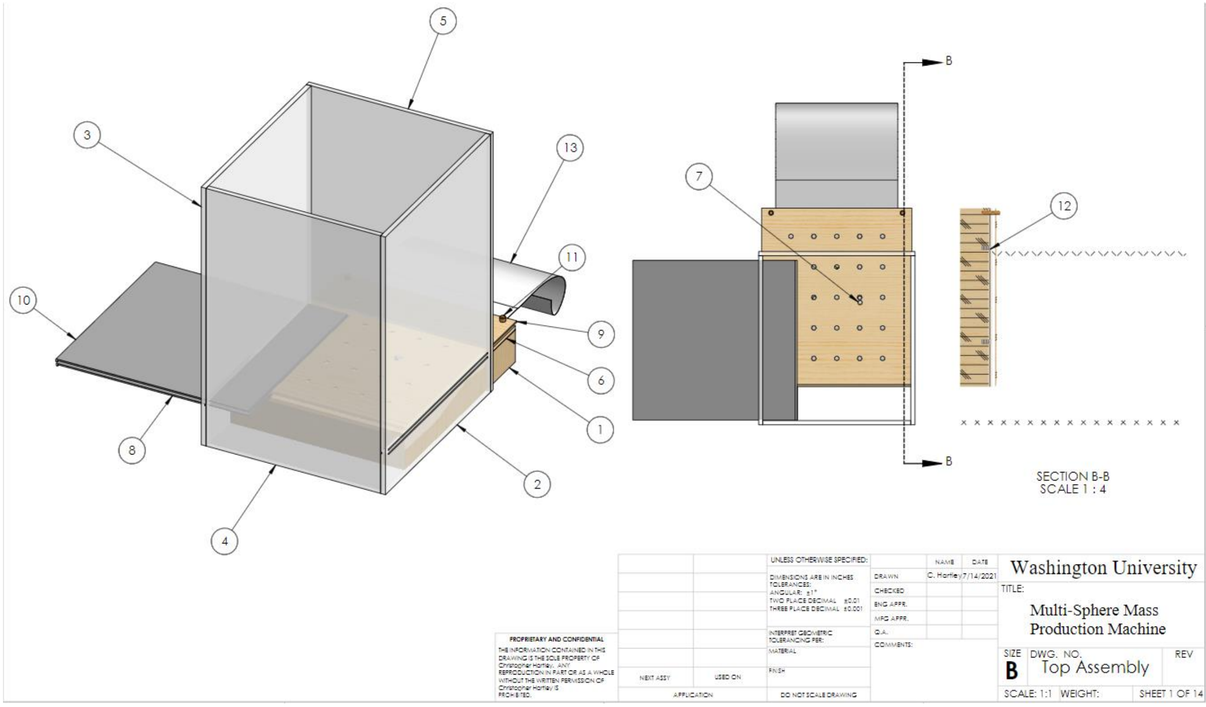


Figure 13: Proposed Final Design Assembly Detail Drawing

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Base Plate	2"x10"x7.875" Wood	1
2	Hopper Right Side Panel	0.22" Thick Plexiglass	1
3	Hopper Left Side Panel	0.22" Thick Plexiglass	1
4	Hopper Back Panel	0.22" Thick Plexiglass	1
5	Hopper Front Panel	0.22" Thick Plexiglass	1
6	Lower Mold	0.1875" Thick Wood with 0.55" Holes	1
7	Porelain Sphere	6 mm Porcelain Spheres	12
8	Separator Plate	0.0625" Thick Plastic Sheet	1
9	Upper Mold	0.0625" Thick Wood with 6 mm Holes	1
10	Upper Separator Plate	0.0625" Thick Plastic Sheet	1
11	0.25 inch Dowel Pin	0.25" Wooden Alignment Pins	2
12	SSFLATSKT 0.25-20x0.5-HX-N	1/4"-20 Hex Head Set Screws	4
13	Parchment Paper	5" Wide Strip of Parchment Paper	1

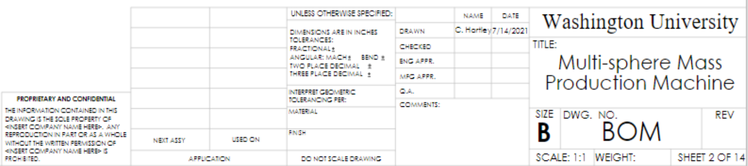


Figure 14: Proposed Final Design Bill of Materials

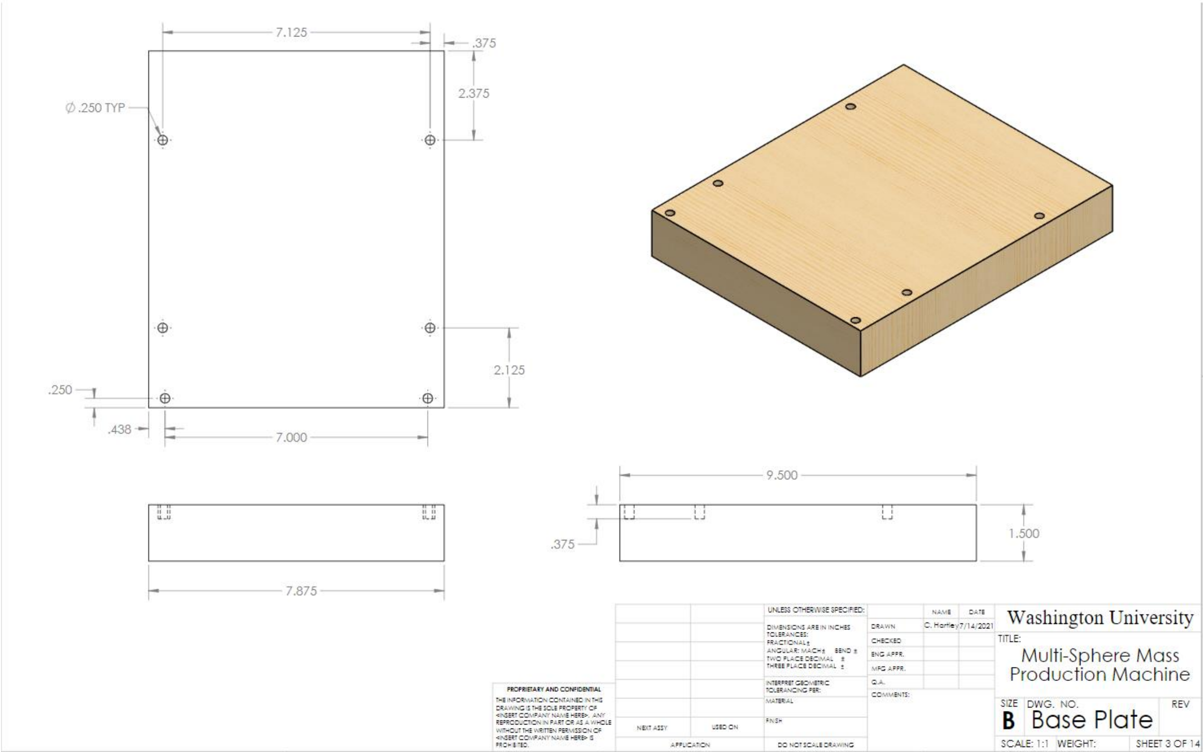


Figure 15: Proposed Final Design Base Plate

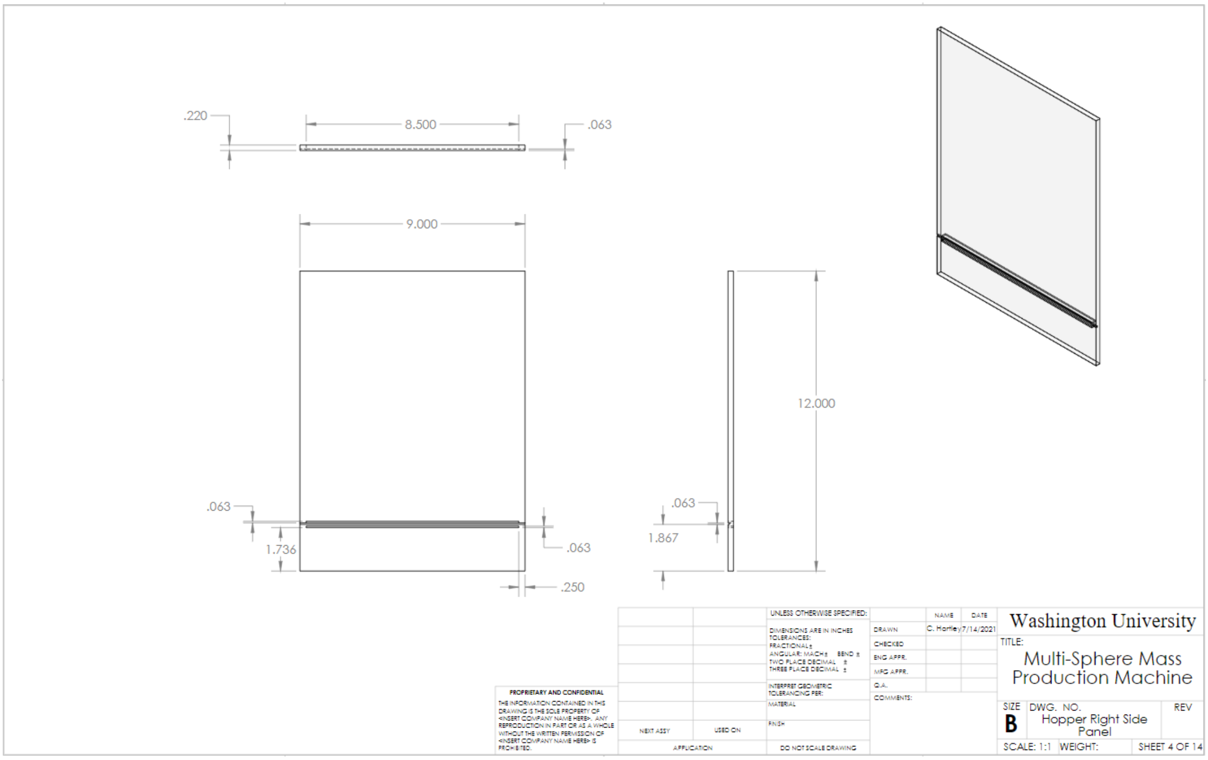


Figure 16: Proposed Final Design Hopper Right Side Panel

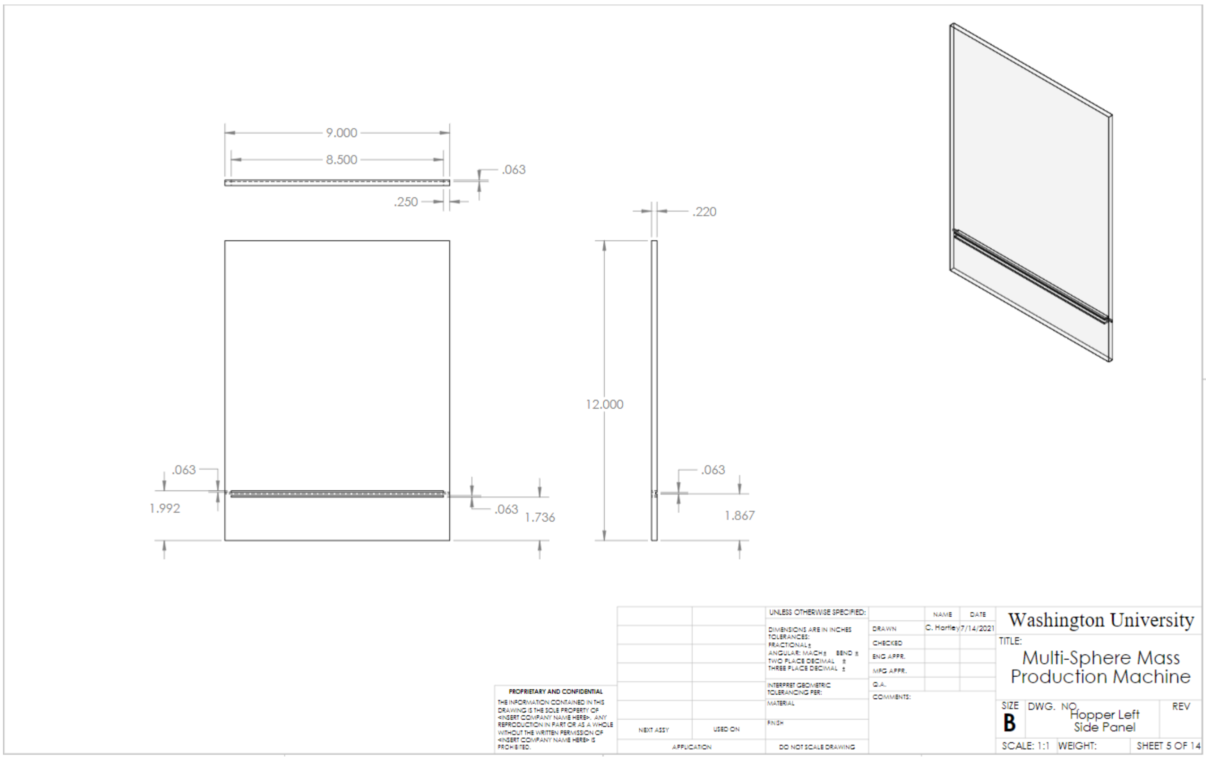


Figure 17: Proposed Final Design Hopper Left Side Panel

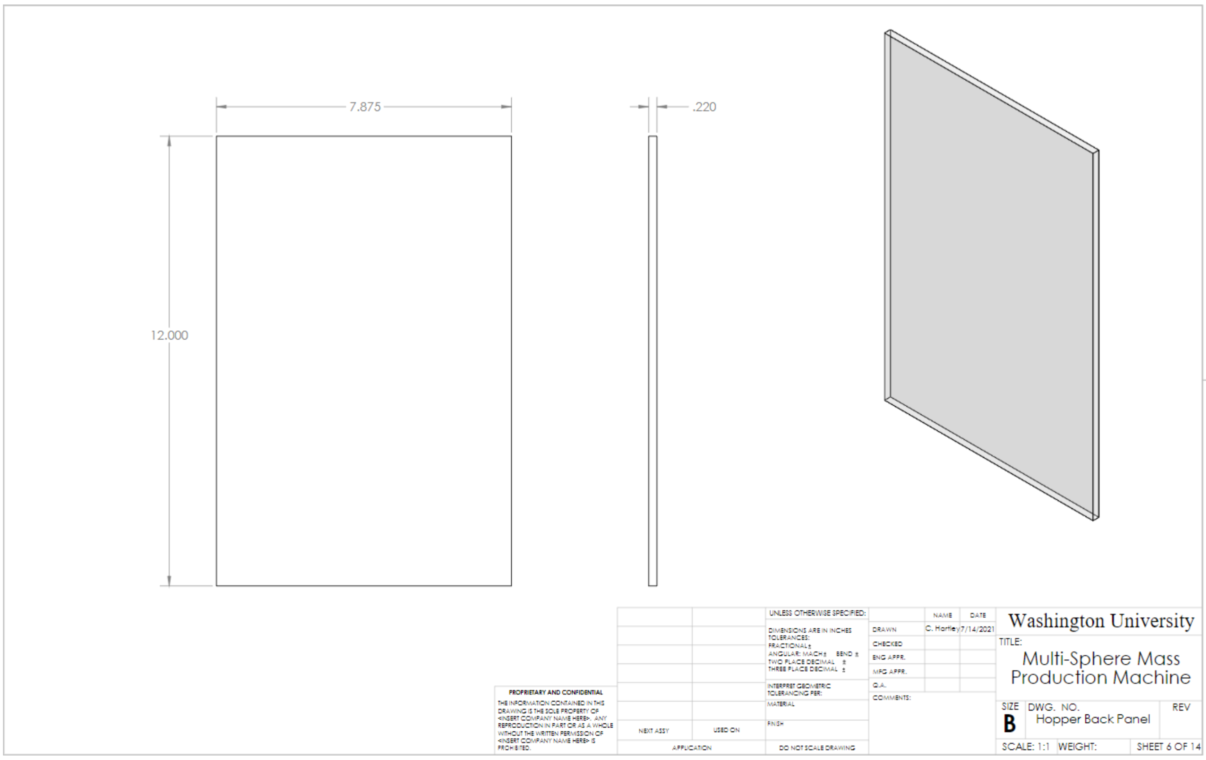


Figure 18: Proposed Final Design Hopper Back Panel

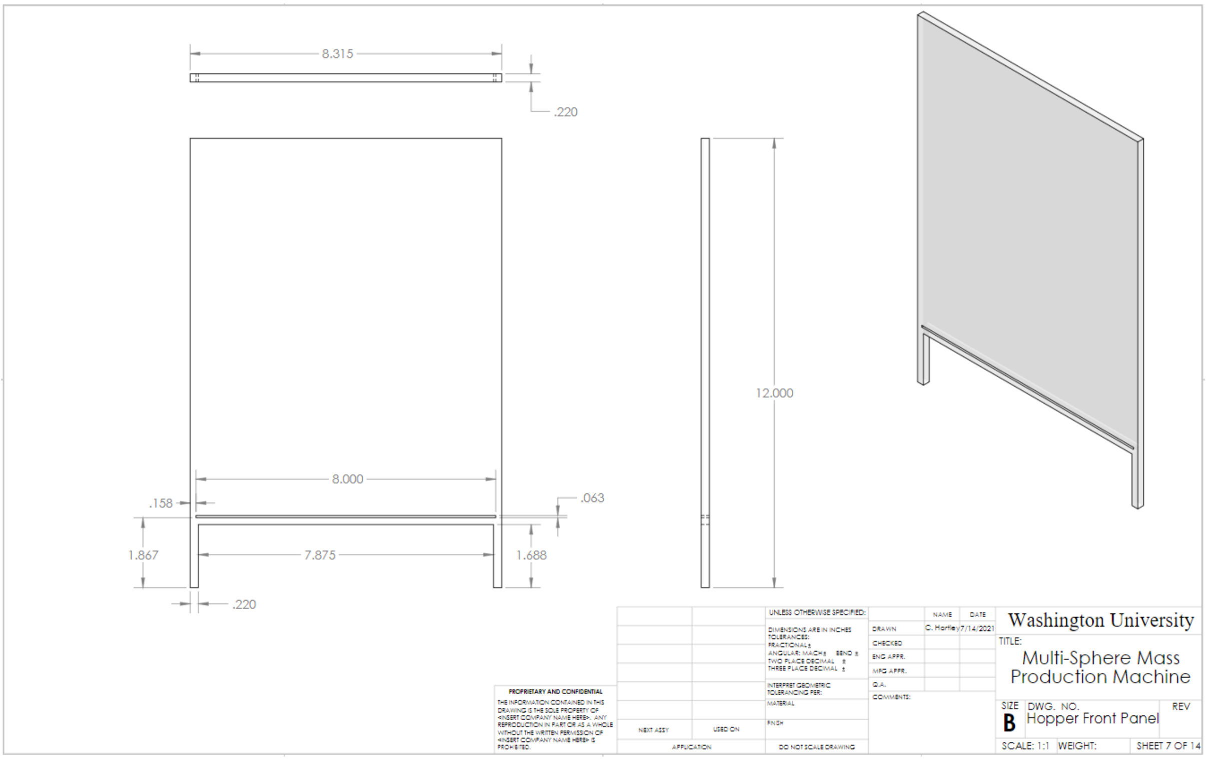


Figure 19: Proposed Final Design Hopper Front Panel

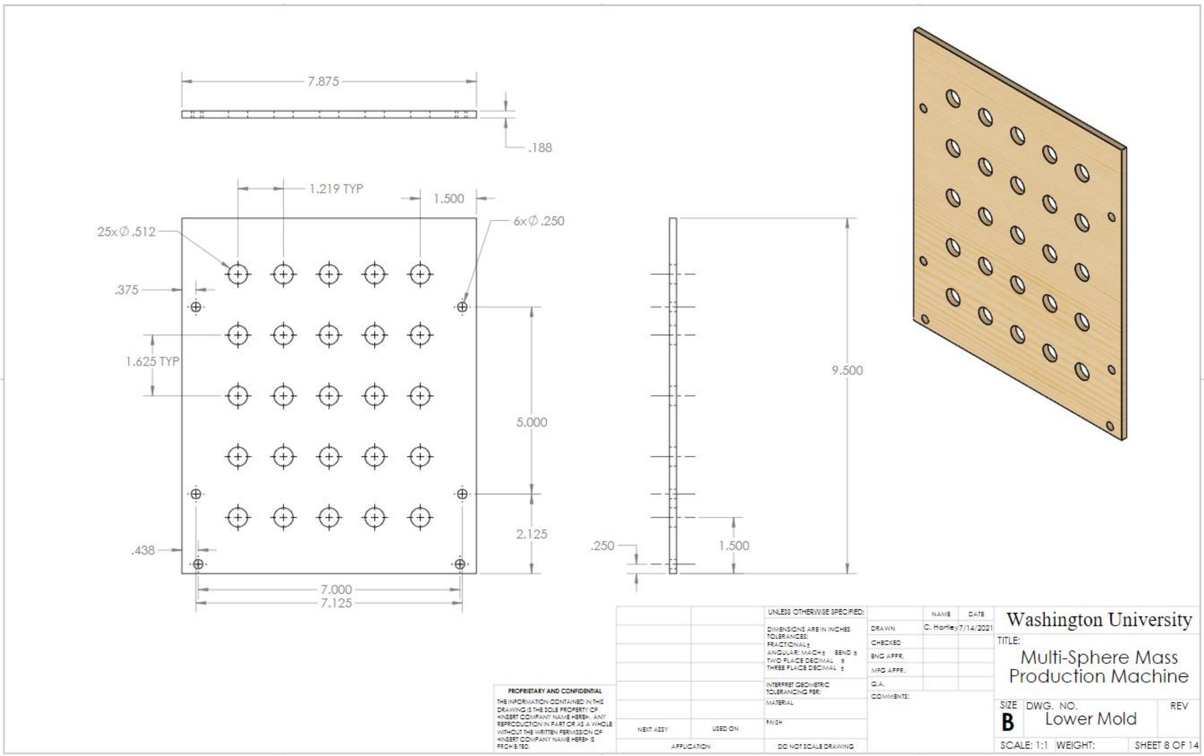


Figure 20: Proposed Final Design Lower Mold

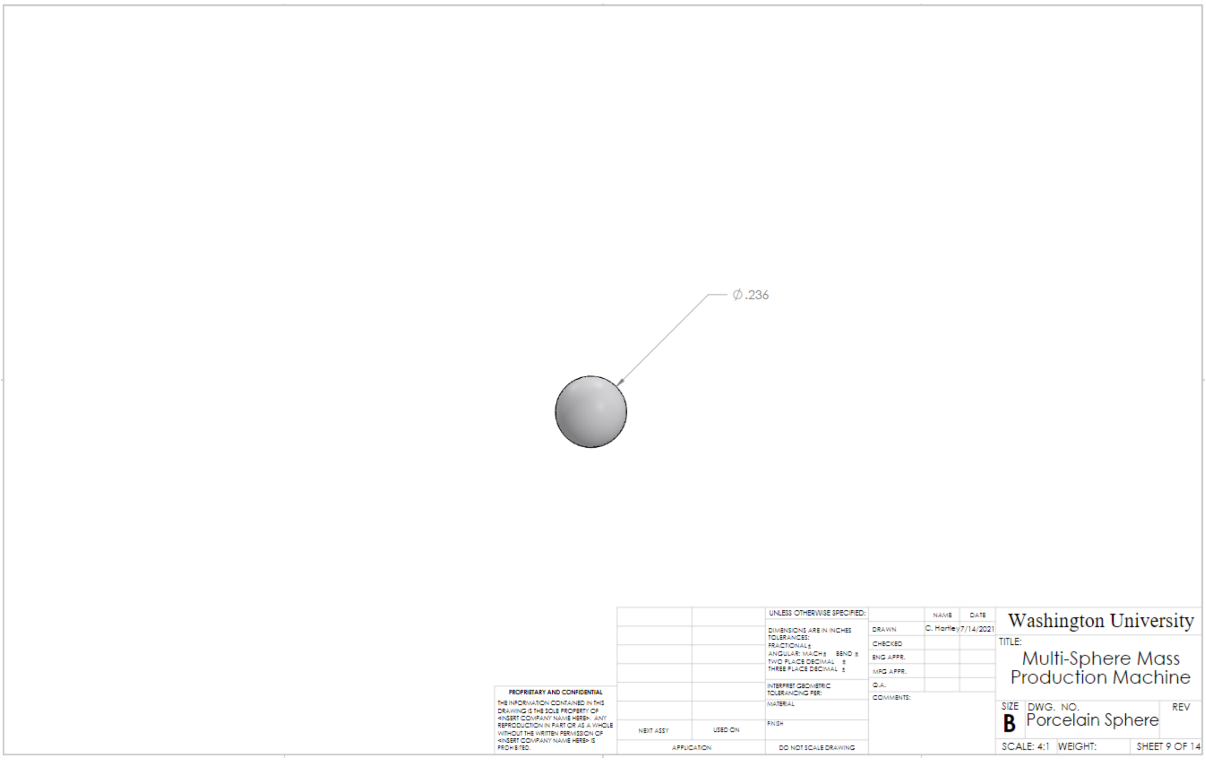


Figure 21: Proposed Final Design Porcelain Sphere

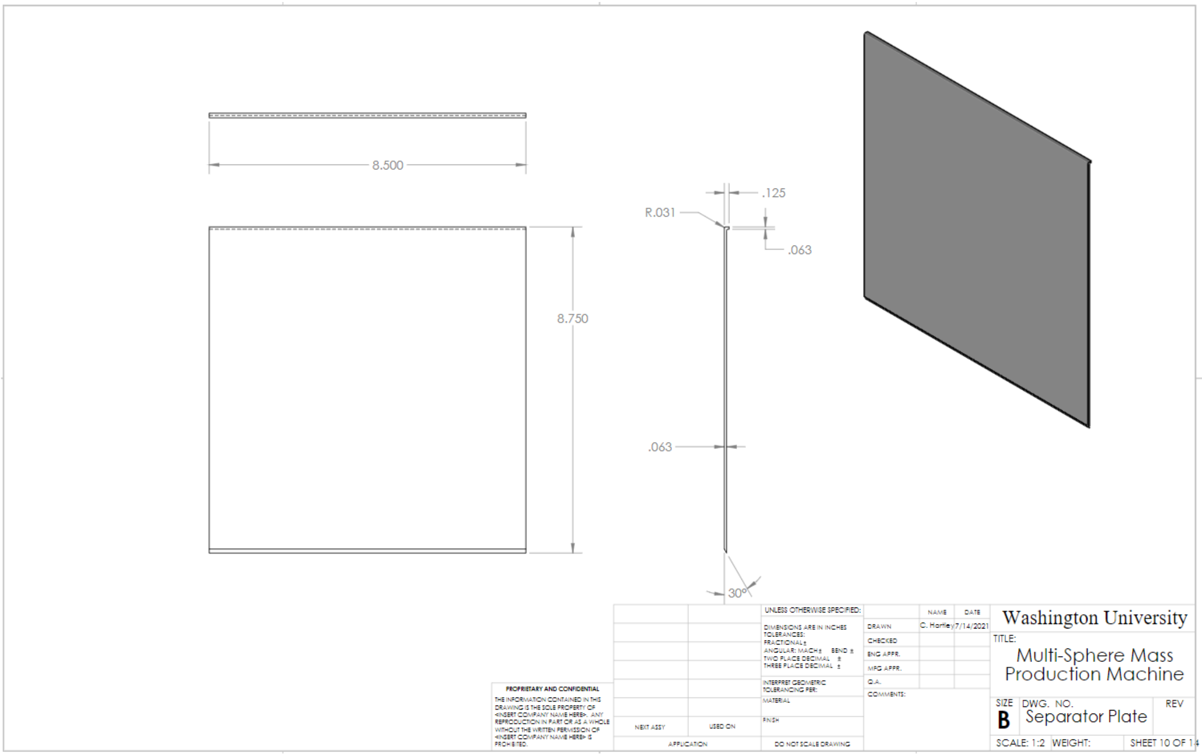


Figure 22: Proposed Final Design Separator Plate

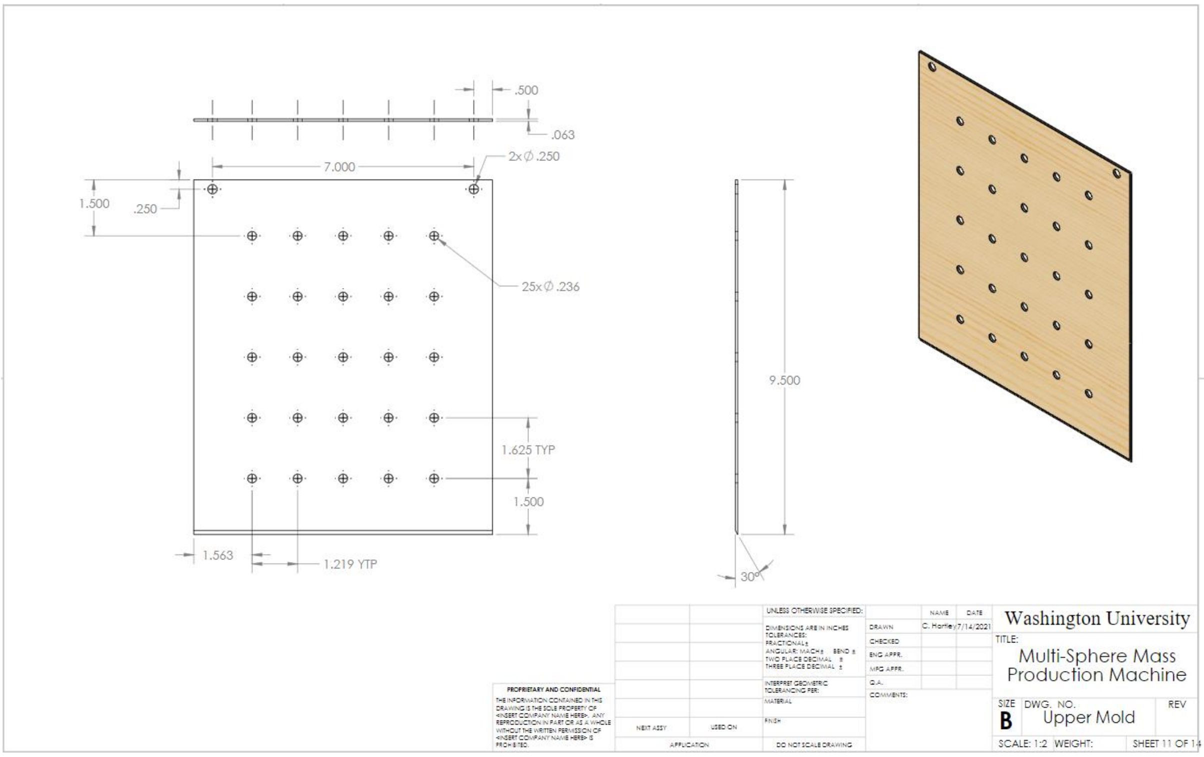


Figure 23: Proposed Final Design Upper Mold

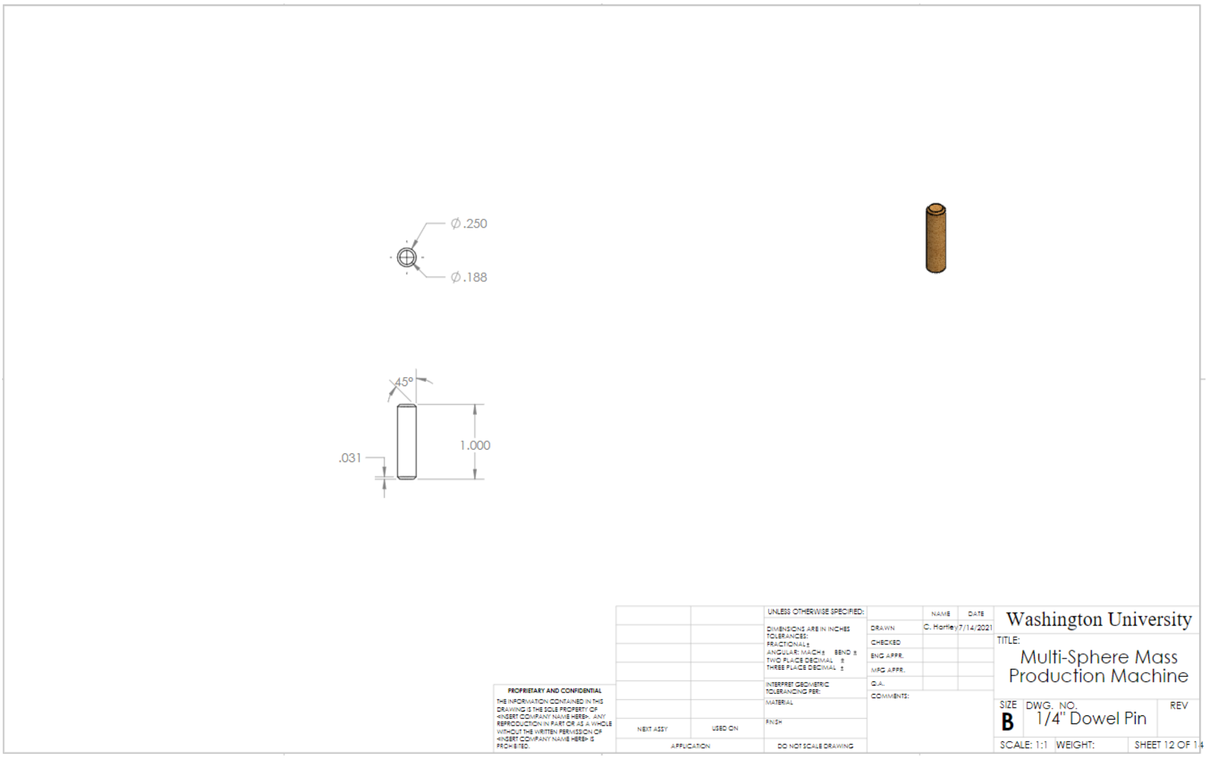


Figure 24: Proposed Final Design 1/4" Dowel Pin for Mold Alignment

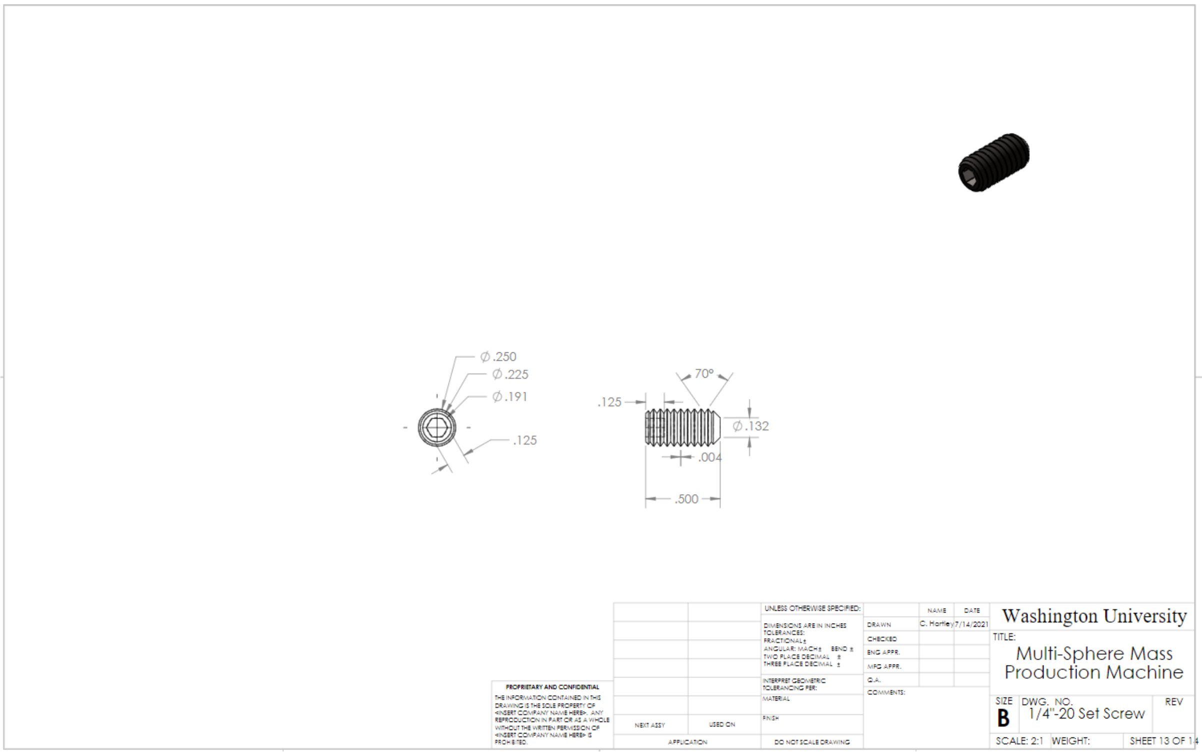


Figure 25: Proposed Final Design 1/4" - 20 Set Screw

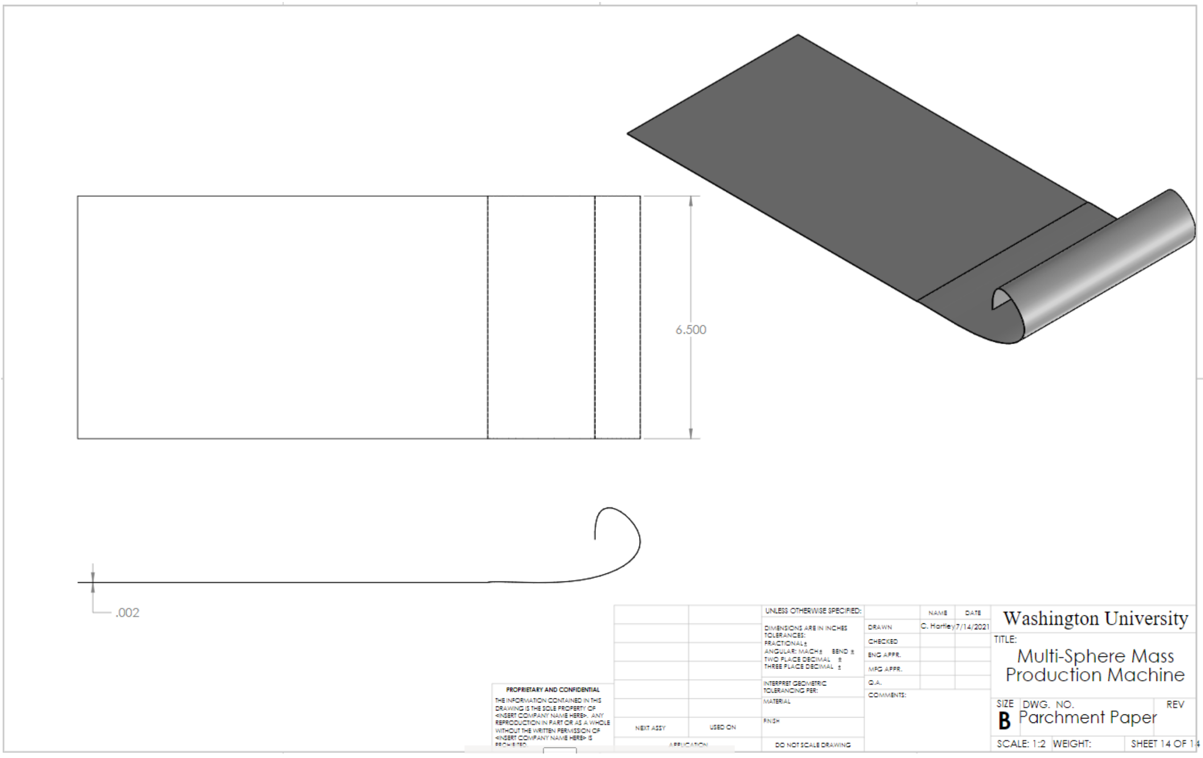


Figure 26: Proposed Final Design Parchment Paper

4.4 DESCRIPTION OF THE DESIGN RATIONALE

Design Rationale

Sphere Selection:

The diameter of the spheres was constrained largely by cost. The ideal diameter of the intrinsic spheres would be 10 mm for ease of construction, but the cost of spheres of this size that also meet the material property requirements set forth in assignment 3 were significantly higher than the required $0.05 per tetrahedral part. The material chosen for the spheres was solid porcelain because both its density and elastic modulus fit snuggly within our acceptable range, determined by the variety of rocks found in Midwestern rivers that are to be modeled, as explained in assignment 3.

Mold Selection:

The chosen material for the upper and lower molds is MDF based on its low cost. There are contingency plans in place if the spheres have an overwhelming tendency to bond to the molds. The thickness was chosen to be 3/16" (4.76 mm), which is greater than the sphere radius, but less than its diameter. There are two reasons for choosing this thickness for the lower mold: 1) so that when glue is placed atop the base trio of spheres, the spheres stick up above the upper face of the lower mold enough that glue does not easily bond the spheres to the mold, and 2) the lower separator plate can be slid into the hopper tangent to the lower trio of spheres while the leading tapered edge of the separator plate remains below the midpoint of any spheres remaining on the mold's upper face, allowing the excess spheres to be pushed up back into the hopper. The thickness of the upper mold was chosen simply to use the leftover material from the sheet used to make the upper mold, since MDF is typically purchased in relatively large sheets (six times the size of the molds being used).

There are two potential methods of construction for the mold plates. The first method is a conventional drilling technique where the plates attached face-to-face after being cut to size. A 1 to 1 scaled drawing of the hole pattern can then be used as a stencil to drill the smaller upper mold holes through both plates. After the plates are separated, the existing holes in the lower mold will be used as center marks to bore the required larger holes. This method is simple, but time consuming for many holes.

The second method uses a sort of DIY CNC engraver called a Maslow CNC. The Maslow requires that the hole pattern be redrawn in .SVG file format and then converted to G-code. The Maslow also uses a hand-held router mounted to a wooden "sled" that is moved about a vertical sheet of wood by a set of chains, which are controlled by two stepper motors (click here or here for more information on the Maslow CNC) The benefits of this method are 1) the CNC is already in the group's possession, so it would not be included in the cost of materials, and 2) were more molds needed, they could be replicated in a fraction of the time required by the first method described above. The downside of this method is that the sled needs to ride over a flat surface about six inches larger in each direction than the piece it is cutting, which means a large fixture will need to be fabricated to hold each work piece in place. Another slight setback is that this method requires more time up front for design and fabrication, so it is not practical for making a one-off part.

Separator Plate Selection
The material specified for the separator plates is solid PTFE plate with the thought that when the lower separator plate is inserted above the lower mold after glue is applied, there is a very high likelihood that glue will contact the separator plate. PTFE is known for (among other things) its non-stick properties, even with super glue. It is also very stable, and consequently is not especially cheap or clean to produce. Before purchasing this material, the team will first test the effectiveness of attaching a thin PTFE sheet to the surface of an ABS plate. If this proves ineffective, a purchase order for the solid PTFE plate will be submitted.

The length and width dimensions for the separator plate were determined by the dimensions of the hopper such that there is enough space to slide the separator plate in and out, but not enough space on either side of the plate to allow spheres to fall past it. The thickness was set to 1/16" as this should be thick enough to remain rigid under the load of a full hopper, but thin enough to "cut" between two layers of spheres as it is inserted.

Parchment Paper Selection
Parchment paper was selected as part of this design to catch any glue that may seep between the base trio of spheres onto the base plate. Thin PTFE sheets were also considered, but there is a risk that glue would build up over time on the PTFE sheets, requiring them to be changed out. The vast price difference between these sheets and parchment paper made it an easy choice to use parchment paper as a semi-consumable separation layer between the lower mold and the base plate.

Hopper Selection
Clear acrylic was chosen as the material for the hopper walls simply so the success or failure of each step of the manufacturing process can be observed in real time. If needed, the cost of material can be reduced by building the hopper out of plywood.
The size of the hopper was determined by the footprint of the molds. The molds hold twenty five (25) parts at a time with adequate space between parts to prevent them from sticking to each other. The height of the hopper is twelve inches (12"), which is almost fifteen times the height needed to hold the required four thousand (4,000) spheres per batch. This is another area where cost can be reduced if needed.

Base Plate Selection
The base plate was determined to use a 2x10 piece of lumber cut to eight inches long simply because there is one available for free to the group. The cost for this part is included in the bill of materials so that the design and cost can be replicated if someone were to choose to build this contraption. The design can easily be modified to use different dimensions and types of materials for the base plate and most other parts in the assembly. There will be two wooden dowels that can be inserted through the upper and lower molds and into the base plate to hold the holes in the molds in alignment with each other.

Set Screw Selection
To keep the parchment paper in place during part construction, set screws will be inserted through the lower mold and into the base plate, clamping the parchment paper between them. The set screws listed in the bill of materials above were selected for their low cost and extremely low profile. If these screws do not work as planned (tapping threads into wood is not always reliable), the screw holes in the lower mold can be countersunk to allow wood screws to be used in place of the set screws.

5 ENGINEERING ANALYSIS

5.1 ENGINEERING ANALYSIS PROPOSAL

5.1.1 Signed engineering analysis contract

PROJECT: Multi-Sphere Mass Production INSTRUCTOR: Mark Jakiela, Craig Giesman

NAMES: Chris Hartley CEH

Chad Gorski CJG

Matthew Brady MLB

The following engineering analysis tasks will be performed:

1. Required hopper volume to hold 4,000 spheres having a 6mm diameter
2. Part volume given sphere diameter
3. Target density of parts based on range of gravel density
4. Target elastic modulus based on range of river pebble elastic moduli
5. Required adhesive bonding strength based on weight of full hopper of parts
6. Structural calculations for the hopper (shear stresses, outward pressure, etc.)
7. Time before parts bond to fixture
8. Quantified consumables during production (wax paper, glue, etc.)
9. Quantified part composition and variation by weight (i.e., percent bonding material)

The work will be divided among the group members in the following way:

Chris Hartley: 3, 4, 5

Chad Gorski: 7, 8, 9

Matt Brady: 1, 2, 6

Instructor signature: Craig J. Giesmann ; Print instructor name: Craig J. Giesmann

Instructor signature: ________________; Print instructor name: ________________

5.2 ENGINEERING ANALYSIS RESULTS

5.2.1 Motivation

There are several variables at play in this design project. The most important deliverables are the speed at which parts can be produced, the accuracy at which the parts model gravel (river pebbles in this case), and the durability of the process. The following list summarizes the analyses that will quantitatively determine the viability of the chosen design:

1. Required hopper volume
2. Part volume given sphere diameter
3. Target density of parts based on range of gravel density
4. Target elastic modulus based on range gravel elastic modulus
5. Required adhesive bonding strength based on weight of full hopper of parts
6. Structural calculations for the hopper
7. Time before parts bond to each other and to fixture
8. Quantified consumables during production (wax paper, glue, etc.)
9. Quantified part composition and variation (i.e., percent bonding material)

The first two (2) items can be found very easily once a size of sphere has been chosen. The size will be driven by material cost. The next two items, (density, and elastic modulus) are found in two stages: preliminary (theoretical) and actual (tested). A range of preliminary material properties was determined based on the properties of rocks most likely to be found in river pebble, according to some internet research during the initial design phase. The average of both ranges (i.e., density and elastic modulus) were used as the target values for both properties.

The adhesive chosen to bond the spheres into their final shape was chosen based on two factors. The first factor is the strength requirement to hold the spheres together while being acted on by the weight of a full container of parts (1,000 parts, or 4,000 spheres). The second factor is the bonding time of the glue. The ideal adhesive will bond quickly to non-porous materials such as gravel, and bond much more slowly to porous materials such as particle board.

The size, shape, materials, and configuration of the hopper are based on the stresses induced by a full batch of at least 4,000 spheres. The calculations will determine the required hardware, material thicknesses, and connection types.

Another important consideration for any production process is the actual quantity of consumable and semi-consumable materials. Accurate rates of consumption and production are necessary to determine the net profit of the process per unit. The quantified consumables will include the volume of adhesive used per part, the number of spheres used per part, the number of parts that can be made with a single roll of parchment paper, and the number of batches of 25 parts that can be made with a single mold. The final analysis calculation will determine a quantified degree of variation between parts. This will be done by comparing the mass of completed parts to the mass of the included spheres.

5.2.2 Summary statement of analysis done

The first calculation performed during the initial design phase was the material properties of the spheres. Research was performed on the top ten most common types of rocks found in rivers [12] to determine the density and elastic modulus of each type. The characteristics from engineering toolbox [13] are summarized in Table 5 below.

Table 5: Material Properties of Common River Rocks

	Clear Quartz	Limestone	Granite	Shale	Jasper	Basalt	Schist	Howlite	Agate
Density (kg/m^3)	2650	2000	2750	2670	2650	2900	3000	2580	2630
Elastic Modulus (GPa)	84	35	40	55	80	57	55	48	78

The density values in the table above were averaged to find the target **density of 2650 kg/m^3,** and the target **elastic modulus of 80 GPa** was chosen based on the user need that the modeled parts must be collide elastically with one another. The material that best fit the material characteristics above while remaining within the budget constraint was found to be 6 mm porcelain spheres originally intended to be used as an abrasive tumbling media.
After settling on a sphere material and size, the part volume can easily be calculated using the equation in Figure 27 below.

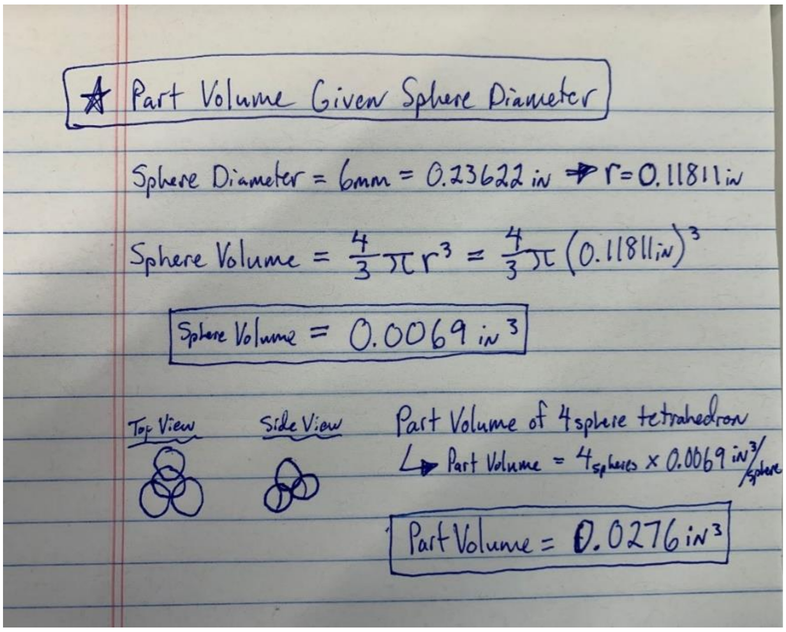


Figure 27: Part Volume Calculations

One of the critical constraints of this process is the ability to produce ten finished parts per minute for a batch of 1,000 parts. The quickest setting glue that was easily accessible and within the required price range has a set time of 10-45 seconds. To increase the chances of meeting the time constraint, the team decided to use a hopper-fed system of molds capable of producing 25 parts per run. Allowing for space between each part in the molds, the mold dimensions were set to about 8” x

8”. These dimensions were then used to calculate the required height and volume of the hopper to hold a batch of 4,000 spheres and thus produce 1,000 parts. Figure 28 below shows the calculations performed to determine the minimum hopper volume.

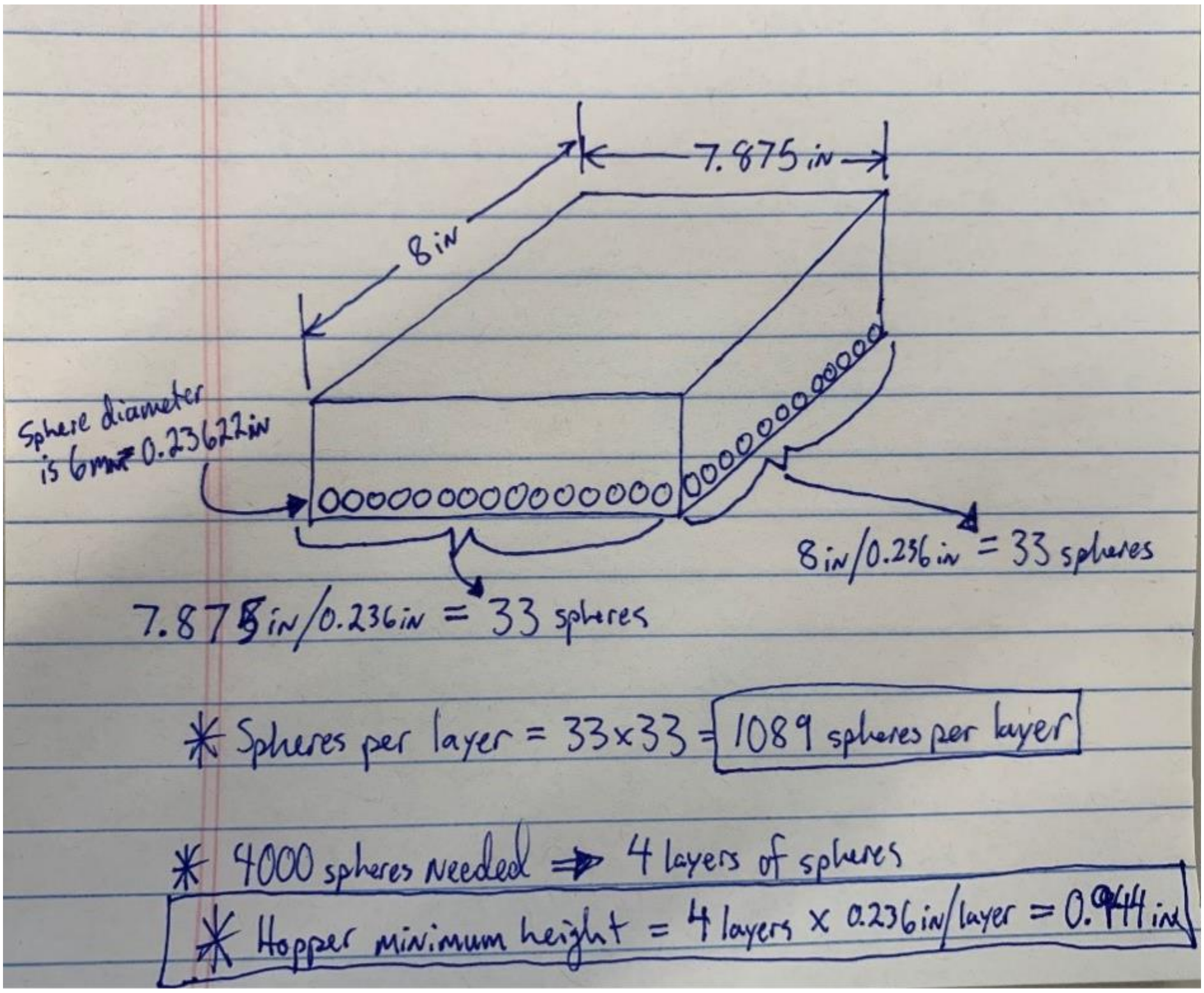


Figure 28: Hopper Volume Calculations

With the density of the porcelain spheres assumed to be 2400 kg/m^3, the weight of each sphere is a simple calculation shown in Figure 3 below. The total weight of 4,000 spheres can then be used to calculate the stress and maximum deflection of the 1/16” thick ABS plastic sheet (separator plate) upon which the spheres will rest. The deflection calculations are given in Figure 30.

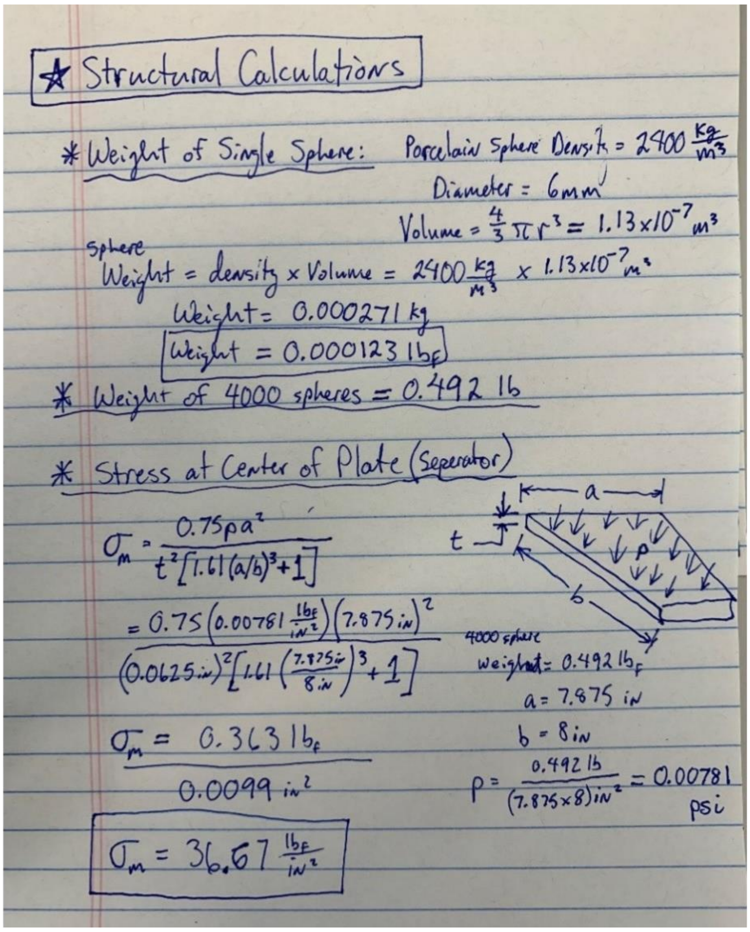


Figure 29: Structural Calculations for Hopper and Parts - Part 1

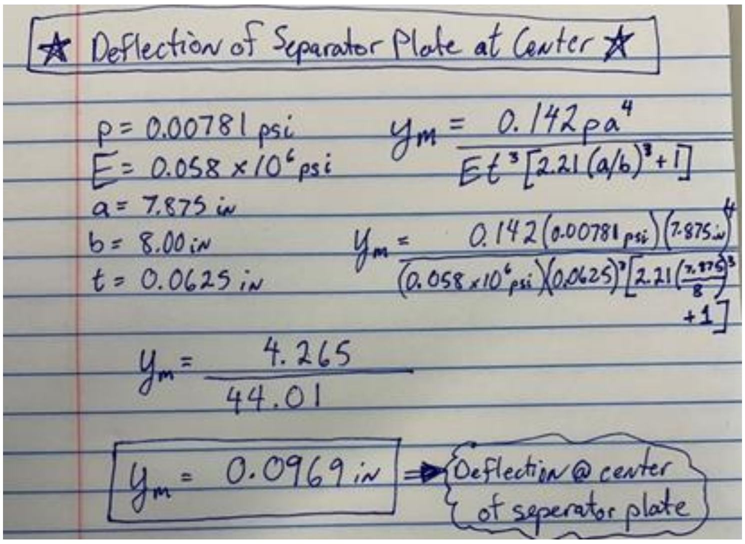


Figure 30: Structural Calculations for Hopper and Parts - Part 2

The amount of glue used per part can be found by simply subtracting the weight of four individual spheres from the final weight of a completed part. This will be repeated with the final weights of about 50% of the parts produced to determine an average number of parts that can be produced per bottle of super glue, as well as the standard deviation of the part weights. The amount of parchment paper used per 25 parts is assumed to be roughly 6” x 8” and will be replaced for each round. The lower MDF mold will be inspected between each batch of 25 parts to determine if glue build-up requires it to be replaced. The bonding times will be determined experimentally for both sphere-to-sphere bonding and sphere-to-mold bonding. If the sphere-to-sphere bonding time is not substantially shorter than the sphere-to-mold bonding time, further analysis will be required to determine an adequate mold material.

5.2.3 Methodology

Bonding Times

A simple experiment has been devised to test the time before which the porcelain spheres will bond to the MDF base mold. A test fixture was constructed out of MDF to hold a row of 5 individual spheres, as shown in figure 5 below. The following procedure details the steps taken during the experiment.
Procedure:

1. Place one 6mm porcelain sphere each into all five of the 7mm holes cut into a piece of 3/16" MDF board resting atop a piece of parchment paper. See figure 5 for details.
2. Apply a single drop of Gorilla super glue between the first sphere and the MDF fixture and immediately press start on a stopwatch.
3. After 10 seconds, attempt to remove the glued sphere from the fixture.
4. Repeat steps 1-3, increasing the time between glue application and part removal by 2 seconds.
5. Repeat step 4 until the spheres cannot be cleanly removed from the fixture.
6. Clean the spheres of glue and repeat steps 1-4 to verify the determined time to adhere to the fixture.

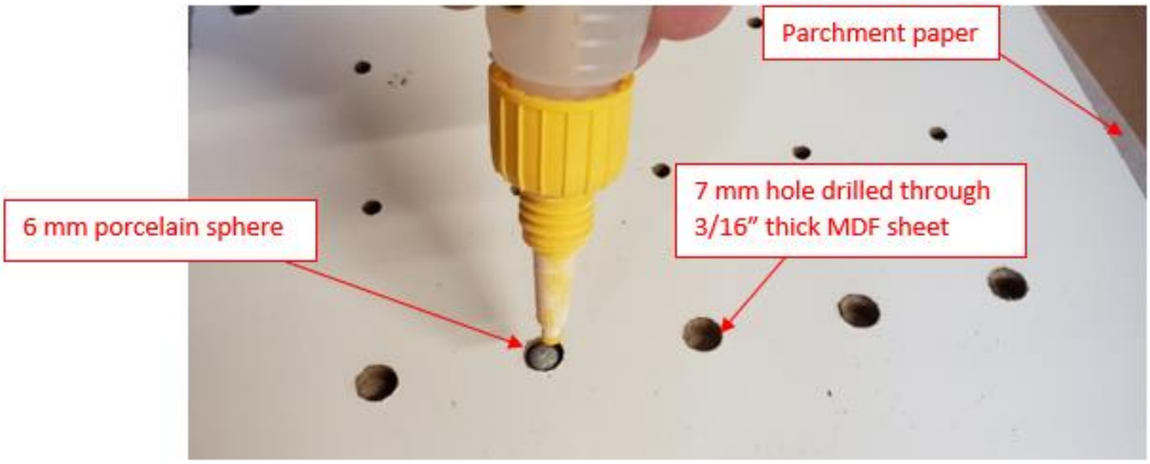


Figure 31: Bonding Time Test Setup

The sphere-to-sphere bonding time was determined in a similar manner, except the actual lower mold with 14 mm holes was used to hold 3 base spheres while the fourth sphere was manually glued on top.

Part Density

The part density will be determined by weighing the completed parts, measuring the water displaced by a single part, then dividing the empirically determined weight by the volume. This will be repeated for at least 50% of the parts to determine an accurate average density to compare to the target density set in the "user needs and specifications" section. Since the scale available to the team has a resolution of 1 gram and the part weight was estimated to be about 0.22 grams, it is necessary to weight at least ten parts at a time.

Percent Bonding Material

The method for determining the average weight percentage of glue contained in each multi-sphere part is very similar to that of finding the part density as described above. After the weight of a collection of 10 to 20 completed parts is measured, the total weight is divided by the number of parts weighed to obtain the average part weight. This process is repeated for a collection of 20 to 40 individual spheres to obtain the average weight of each sphere. Finally, the average sphere weight is multiplied by 4, divided by the average part weight, and multiplied by 100% to obtain the average percentage of bonding material contained in each part. The weight of the glue needed for each part is then simply the difference between the weight of a final part and the weight of 4 individual spheres.

Structural Calculations

To verify that the separator plate does not deflect more than the predicted 3/32", the deflection will be measured explicitly under a load of about 1,000 spheres. If the deflection is great enough that spheres fall out of the hopper below the top edge of the front window slot, the design will be altered to re-use the separator plate material in a more appropriate design.

5.2.4 Results

Bonding Times

The results of the bonding time experiments for gorilla super glue are summarized in Tables 6 and 7 below.

Table 6: Sphere-to-Mold Bonding Time Results

Trial	Time (s)	Bonded?
1	10	NO
2	20	NO
3	30	NO
4	40	NO
5	50	NO
6	60	NO
7	70	NO
8	80	NO
9	90	NO
10	----	NO
11	120	Slightly

Table 7: Sphere-to-Sphere Bonding Time Results

Trial	Time (s)	Bonded?
1	5	NO
2	10	YES
3	15	YES

Based on the results above, the maximum target time between applying glue and removing the completed parts will be 1 minute.

Part Density

Based on the methods described in the previous section, the average part volume was measured to be 1.2 g per part, with an average volume of 0.57 ml, which gives an average density of 2,100 kg/m^3. This is withing 15% of the theoretical density and falls within the acceptable range.

Percent Bonding Material

The percent bonding material was calculated using the methods of the previous section for a total of 3 batches of parts. The parts tested contained between 4 and 6 % glue by weight, with an average of 4.8 %, which is below the maximum allowable percentage.

Structural Calculations

Unfortunately, the separator plate deflected by about ½”, which is more than 5 times the allowable deflection. This likely happened because as the plate began to deflect, spheres tended to concentrate towards the lowest point, voiding the perfectly distributed load assumption made in the theoretical calculations. The over deflection resulted in spheres pouring out through the front of the hopper when the mold assembly was removed. The parts that did make it into the molds remained intact and in the correct configuration. The modifications to the hopper structure and sphere application process are discussed further in the “significance” section below.

5.2.5 Significance

Most of the analysis yielded results that were on par with what was predicted. The design was not influenced by any of the performed experiments, except for the separator plate deflection test. The failure of this test forced the design team to take a significant step back and rethink how excess spheres would be removed from each mold.

With the separator plates no longer usable as designed, an additional support structure was built to allow the molds to be tilted, catching excess spheres in a container below for future use. The elimination of the separator plates also necessitated cover plates for the empty slots that the plates would have slid through. Fortunately, one of the separator plates was able to be repurposed as a guide plate to funnel the excess spheres into a container as they spill out from the bottom of the hopper, as shown in Figure 32 below.

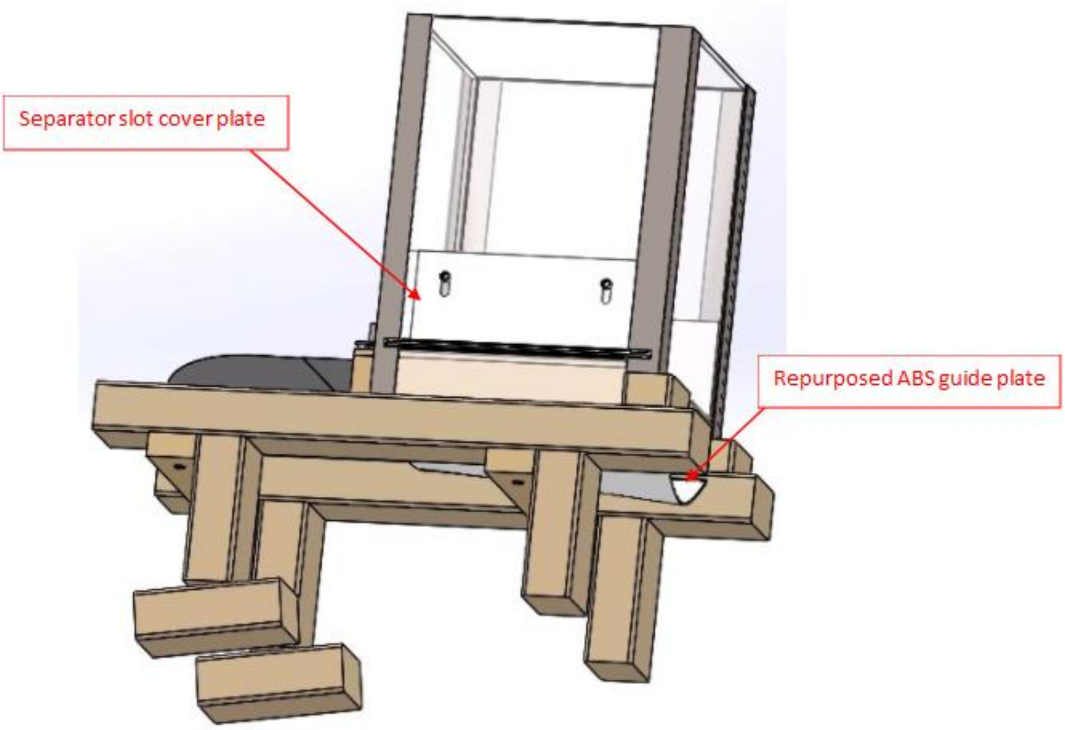


Figure 32: Post Analysis Design Implementation

6 RISK ASSESSMENT:

Table 8: Risk Management Register

Risk Management Register

0	Open Red Risks
0	Open Yellow Risks
0	Open Green Risks
0	Risks w/ no Response Strategy
0	Closed risks

Project Name:
Project Manager:
Start Date: 6/14/21

Location: Saint Louis
Add'l Info: Tetrahedron Design
Updated On: 7/21/21
Overall Project Risk Indicator: 4

Risk Level

Probability					
5	5	10	15	20	25
4	4	8	12	16	20
3	3	6	9	12	15
2	2	4	6	8	10
1	1	2	3	4	5
	1	2	3	4	5

Impact

Legend:
Impact
1 - Negligible
2 - Marginal
3 - Significant
4 - Critical
5 - Catastrophic

Probability
1 - Rare
2 - Unlikely
3 - Possible
4 - Likely
5 - Certain

Item	Project/Phase	Risk Status	Risk	Potential Impact (Cause and Effect)	Risk Response Strategy	Triggers/Indicators that the risk will occur/	Estimated Schedule Impact (Days)	Maximum Exposure ($000)	Estimated Exposure (Contingency) ($000) $71	Risk Category	Risk Sub Category	Action Owner	Start Exposure	End Exposure	Baseline Risk Scoring: Impact: Tech Perf	Schedule	Cost	Safety	Probability	Risk Ranking	Current Risk Score: Impact: Tech Perf	Schedule	Cost	Safety	Probability	Risk Ranking
1			Schedule	Deadlines and scheduled meetings could be missed. Team members might have varying availability week to week making it difficult for the full group to meet.	Remain flexible and dedicated to attendance agreements. Communicate and have backup plans or shorthanded meetings to maintain project progress.	Increased time requirements for other aspects of life. Family-work life-school balance.	3	$52	$1	Schedule	Labor Availability	Project Manager/Team	06/14/21	08/16/21	0	3	3	0	2	6	0	3	3	0	1	3
2			Codes and Standards	Incorrect, invalid, or delayed codes or standards would delay prototype development and/or testing. If project were to proceed without proper codes and standards, it could result in legal penalties or project cancellation. Huge cost and time impact, as well as ethical and safety concerns.	Have multiple engineers review the code and standard requests for accuracy and application to the specific project and prototype plans. Take advantage of the assistance from Lauren (Todd?).	Missing or inaccurate information as well as previous experience requesting codes and standards.	7	$126	$3	Project Development	Terms & Conditions Acceptable	Project Manager	06/28/21	08/16/21	1	3	3	4	2	8	1	3	3	4	1	4
3			Tornados	High winds and storms could badly damage equipment or manufacturing location, as well as any progress already made, thus heavily delaying the project.	Have weather delays built into the schedule for all types of storms.	Reference government weather data about likelihood of tornados and heavy storms during the time of year the project is done.	14	$200	$5	Schedule	Weather, Site Conditions, Essential Services	Project Team	06/14/21	08/16/21	0	5	1	5	1	5	0	5	1	5	1	5
4			Environmental	Manufacturing process could be bad for the environment, harmful to the project team or detrimental to the manufacturing location.	Have expert investigate codes and standards as well as best practices. Consult on best steps moving forward. Abide by any unforseen code requirements and expedite such work to maintain project schedule.	Previous types of projects incurring the same risk. Advice from professors or third party resources regarding similar processes.	7	$30	$1	Operational Impact	Environmental Impacts	Project Team	07/05/21	08/16/21	0	2	4	4	1	4	0	2	4	4	1	4
5			Rain	Rain can damage equipment or delay starting certain phases of the project increasing cost and delaying project completion	Build weather days into the schedule based off typical rain patterns for the season	Look at local weather patterns and historical data about rain during time of season; might be worth scheduling during specific months (such as summer) to avoid this as best as possible	3	$500	$13	Schedule	Weather, Site Conditions, Essential Services	Project Manager	06/14/21	08/16/21	1	2	1	1	2	4	1	2	1	1	1	2
7			Safety	Injuries during prototype development - potential lifelong injuries; could greatly delay and/or end the project	Train individuals on all necessary safety requirements and follow all of OSHA guidelines and manufacturing safety measures	Team members' previous work experience and the resulting level of safety from prior jobs. Also the team's familiarity with OSHA and manufacturing guidelines	14	$500	$13	Construction	Contractor Safety Program	Project Team	06/28/21	08/16/21	0	5	5	5	2	10	0	5	5	5	1	5
8			Estimating	Miscalculating budgets from bad cost estimates - could lead to tying up too much or too little funds	Use experience of other project managers and/or engineers to narrow the estimates closer to likely values	Project costs are quickly exceeding expected budget, or project costs are coming in far lower than expected at certain checkpoints	3	$500	$13	Financial/Regulatory	Cost, Budget, Forecast in Alignment	Project Manager	06/14/21	08/16/21	1	3	3	1	2	6	1	3	3	1	1	3
9			Delayed Materials Delivery	Issues with manufacturer or material availability might delay delivery of necessary materials, might increase cost to expedite	Have multiple vendors for raw materials such as backups for each key component, and multiple backups for materials that will delay the project longest	Shipping from foreign countries might have long lead times such as weeks or months	14	$500	$13	Schedule	Material Constraints	Project Manager/Team	06/14/21	08/16/21	0	5	4	3	3	15	0	5	4	3	1	5
10			Equipment	Equipment failures or lack of available equipment resources could alter the project schedule and/or delay certain aspects of the project changing the critical path or increasing overall project cost	Plan resources properly and have contingency plans in place to replace failed or delayed equipment. Perhaps short term rental from a local company could offset delays while equipment is out of order.	Equipment availability in the weeks leading up to the project start	5	$100	$5	Schedule	Schedule Requirements Addressed	Project Manager/Team	07/05/21	08/16/21	2	3	4	4	1	4	2	3	4	4	1	4
11			Covid Resurgence	Covid breakout or increase in cases could cause prototype construction meetings cancelled or materials manufacturing to be halted or severely delayed which could stall a project	Have plan in place for operations under a more stringent social distancing mandate. Prepare backup prototype plan accordingly in terms of scheduling and responsibilities.	Local and national news regarding status of Covid; number of project members fully vaccinated	21	$100	$3	Operational Impact	Operational Flexibility	Project Manager	06/14/21	08/16/21	0	4	1	5	2	10	0	4	1	5	1	5
12			Failed Prototype	Prototype fails to live up to the specifications and basis of design required by the customer. Project restart or cancellation.	Meet often with customer to confirm track of progress and ability to achieve goal while remaining within the scope of the project.	Customer dissatisfaction with status updates during regular meetings.	14	$100	$3	Project Development	Scope is Complete	Project Manager	07/12/21	08/16/21	4	5	5	0	2	10	4	5	5	0	1	5

The top risks for the project were adhering to the schedule. This was a result of the vastly different, yet equally demanding, schedules for our project team. Additionally, there was a risk that the prototype would not perform as expected. This risk was realized during our final two weeks of prototyping. To mitigate this risk, our strategy was to test everything at the end of each prototyping day. If something didn't work, we would discuss the problem and brainstorm solutions immediately. This way every team member understood their responsibilities in working towards our solution. The risk involved in this project was relatively low and we exceeded our goal of ten parts per minute.

7 CODES AND STANDARDS

7.1 IDENTIFICATION

ISO/ASTM 52901:2017 [14]

OSHA Standard 1910.212 - General requirements for all machines [15]

OSHA Standard 1926.57 - Ventilation [16]

ISO 83.180 - Adhesives [17]

7.2 JUSTIFICATION

ISO/ASTM 52901:2017

This ISO is identified as the primary driver for commonly accepted processes and practices when purchasing parts made by Additive Manufacturing. It sets forth common terminology, frameworks, inspection criteria and acceptance criteria between the manufacturer and the customer to ensure customer requirements are met. More stringent requirements may be placed on the manufacturer via supplemental requirements by the purchaser at the time of order. This was similar in scope to the customer needs interview process as well as methodology for modifying design to meet shifting customer requirements as they became available.

OSHA Standard 1910.212

This standard identifies OSHA Safety and Occupational Health requirements for machine guarding in industrial environments. This document sets all safety requirements for any tooling required to produce products in a machine shop environment. This was the accepted condition under which it was assumed work would take place for this project. Adherence to this standard was a primary safety requirement for prototype construction during this project.

OSHA Standard 1926.57

This standard identifies OSHA Safety and Occupational Health requirements for general and specific ventilation and exhaust requirements to maintain air quality within the guidelines set forth in OSHA Standard 1926.55(a) - Exposure Limits for Gasses, Vapors, Fumes, Dusts, and Mists. Adherence to this standard ensures the safety of all persons who may be exposed to breathing contaminants at or above the permissible levels for occupational health. This is the driver for our methods of sintering/combining elements for Additive Manufacturing, as well as construction of prototype forms.

ISO 83.180 - Adhesives

This ISO contains testing standards for general adhesives between various materials as well as establishes requirements and accepted methods for preparing adhesive surfaces prior to bonding. Adherence to the standards set forth under this ISO ensure uniformity of prepared surfaces for adhesion and potential sintering (and un-sintering) standards. This ISO also allows us to utilize accepted standards for verifying bond strength and adhesion performance.

7.3 DESIGN CONSTRAINTS

7.3.1 Timing

The manufacture of the sphere assemblies was given a time requirement as set forth by the customer of 1 minute to produce 10 fully assembled sphere tetrahedrons. This is directly impacted by our choice of adhesive, as the maximum time to cure for each assembly to ensure the spheres would not disassociate could be as great as 45 second, per the manufacturer's advertised values. At this maximum value, it is conceivable that our Manufacturing goals would not be met based on cure time alone.

7.4 SIGNIFICANCE

To achieve this value, it was necessary to increase the number of concurrently manufactured sphere assemblies to increase the ratio of units produced vs time to the accepted value prescribed by the customer. The final value was 2.5 times (250%) the required volume, or 25 sphere assemblies per run, to allow for additional timing between manufacturing steps to full cure a volume of assemblies at or above 10 fully assembled sphere tetrahedrons per minute.

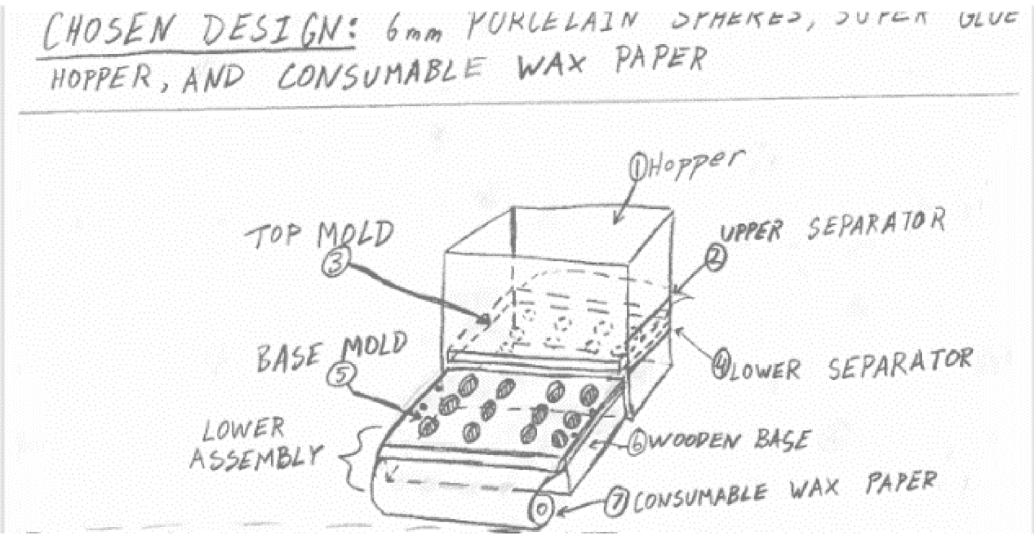


Figure 33: Initial concept design with 12 sphere assembly receptacles

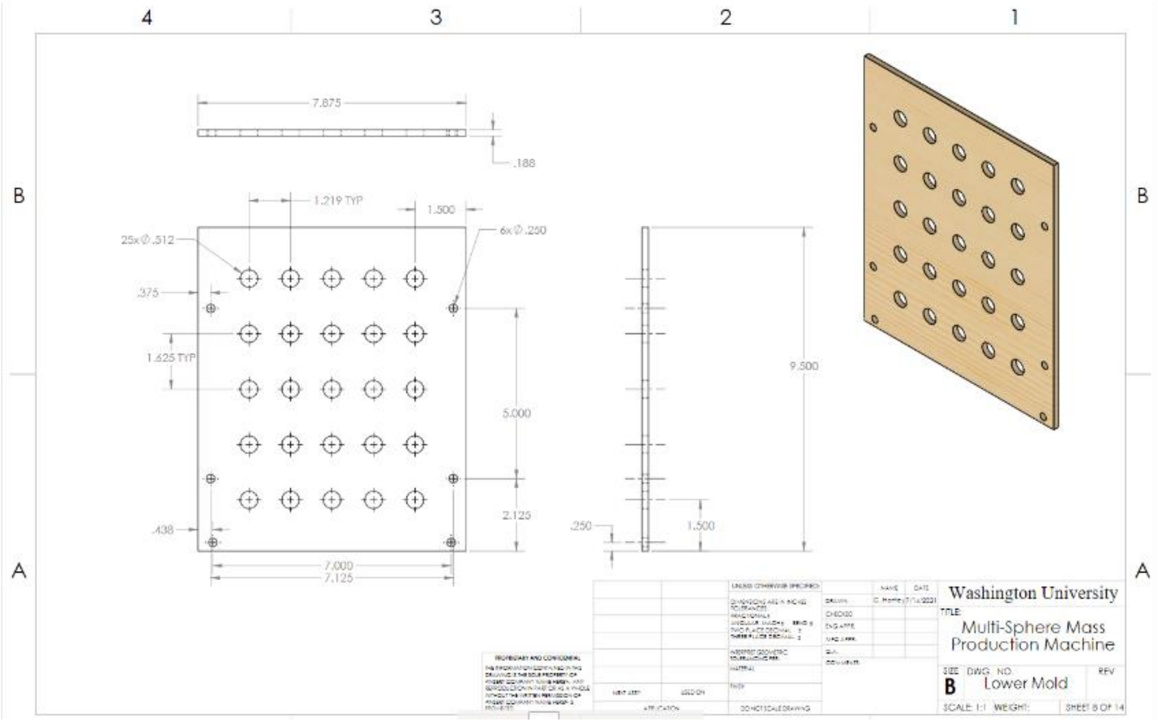


Figure 34: Final Lower Plate Design with 250% required capacity to account for constraint

8 WORKING PROTOTYPE

8.1 PROTOTYPE PHOTOS

Figures 35 and 36 below show the full assembly of the device used to mass produce 4-sphere tetrahedrons composed of 6mm porcelain spheres and super glue. The plexiglass structure directs spheres into a set of molds. The lower mold (white MDF board with drilled holes) is shown in figure 1 fastened to the base plate (2”x10”x8.5” board), resting on top of the base structure. Each hole in the lower mold holds 3 spheres, forming the base of the tetrahedrons. The pieces of black plastic mounted to the side panels of the hopper are part of a previous design and are now used to cover unused slots that were cut for the previous design.

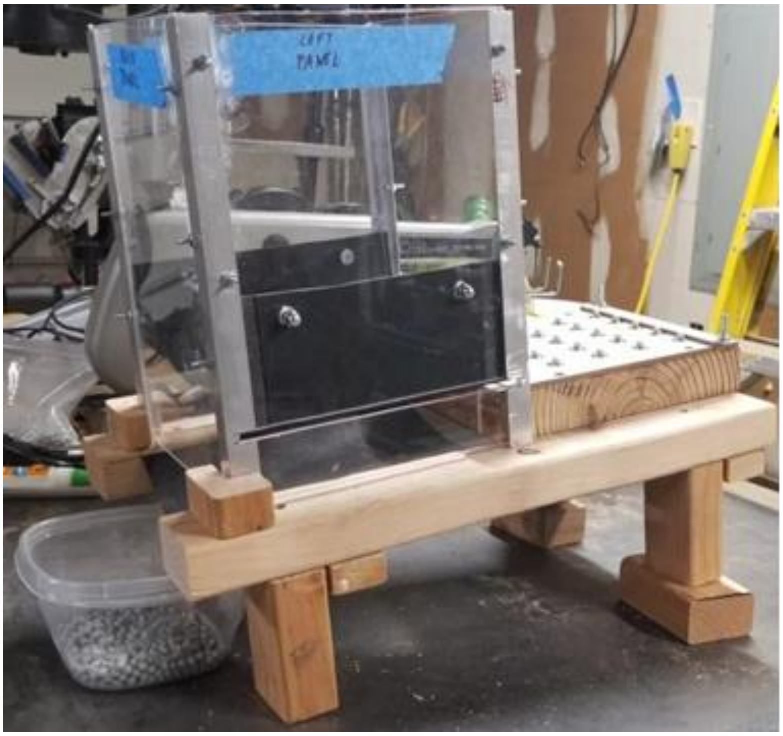


Figure 35: Working Prototype Full Assembly from the Front Left Corner

After applying glue to each trio of spheres, the upper mold (black sheet of ABS plastic shown in the upper left of figure 36) is placed on top to direct the final sphere onto each of the glued sets. Removing the upper and lower molds allows the completed parts to be removed and set aside to fully cure.

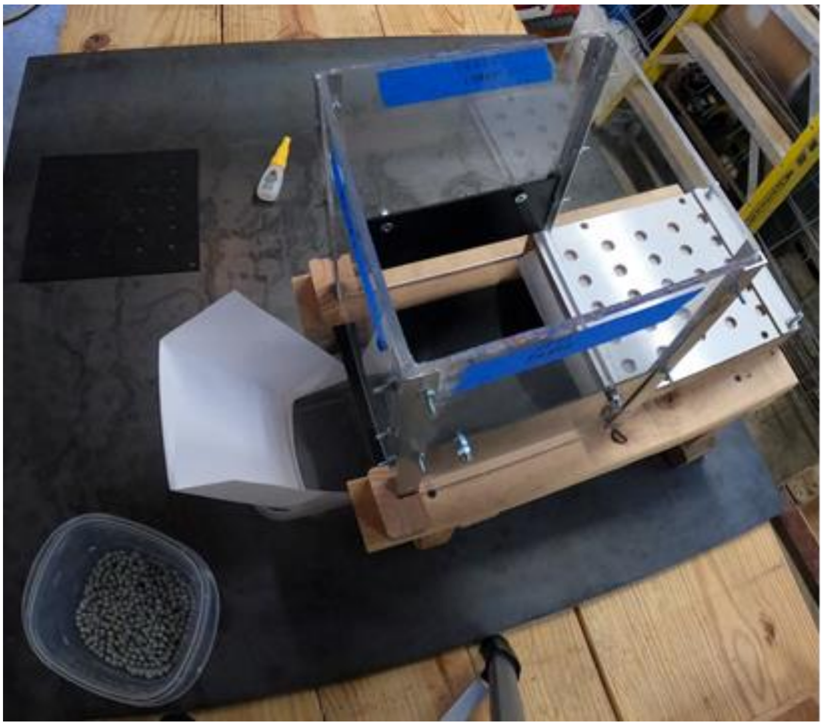


Figure 36: Working Prototype Top View of Full Assembly

8.2 WORKING PROTOTYPE VIDEO

Please follow the link below to see the Multi-Sphere Mass Production Prototype Demonstration video:
https://youtu.be/AOsM9CAQtb0

8.3 PROTOTYPE COMPONENTS

Figure 37 below gives a breakdown of the prototype assembly. The following list explains the significance of each part:

1. The **Base Support** holds the mold assembly and hopper above the sphere collection container.
2. The **Riser Blocks** allow the support structure to be tilted in a controlled way, allowing excess spheres to pour forward off the mold, down the plastic guide plate on the support structure, and into the collection container.
3. The **Base Plate** holds the alignment screws and mounting screw, allowing the molds to remain secure and in proper alignment.
4. The **Separator Sheet** prevents parts from sticking to the wooden base plate when glue is applied
5. The **Lower Mold** holds the lower trio of spheres for 25 parts in the large, drilled holes.
6. The heads of the **Alignment Screws** set into counter-bored holes in the base plate and the threads fit through holes in both the upper and lower molds to keep them in proper alignment with each other.
7. The **Jam Nuts** fasten the alignment screws to the lower mold and provide the proper spacing between the front ends of the upper and lower molds.
8. The **Retainer Screws** fasten the lower mold to the base plate, which holds both the separator sheet and place and the alignment screws in place.
9. The **Super Glue** is applied to the base trio of spheres before the upper mold is applied, bonding the final top sphere in place.
10. The **Upper Mold** contains 25, 7mm holes that are concentric with the holes in the lower mold.
11. The **Hopper** holds an excess number of spheres to increase the likelihood that the entire mold is filled without losing any spheres to the surrounding area.
12. The two **Containers** are alternated between applying spheres to the molds and collecting excess spheres. The sheet of paper shown in the right-most container is to ensure that no spheres bounce over the container as the mold assembly is removed from the hopper.

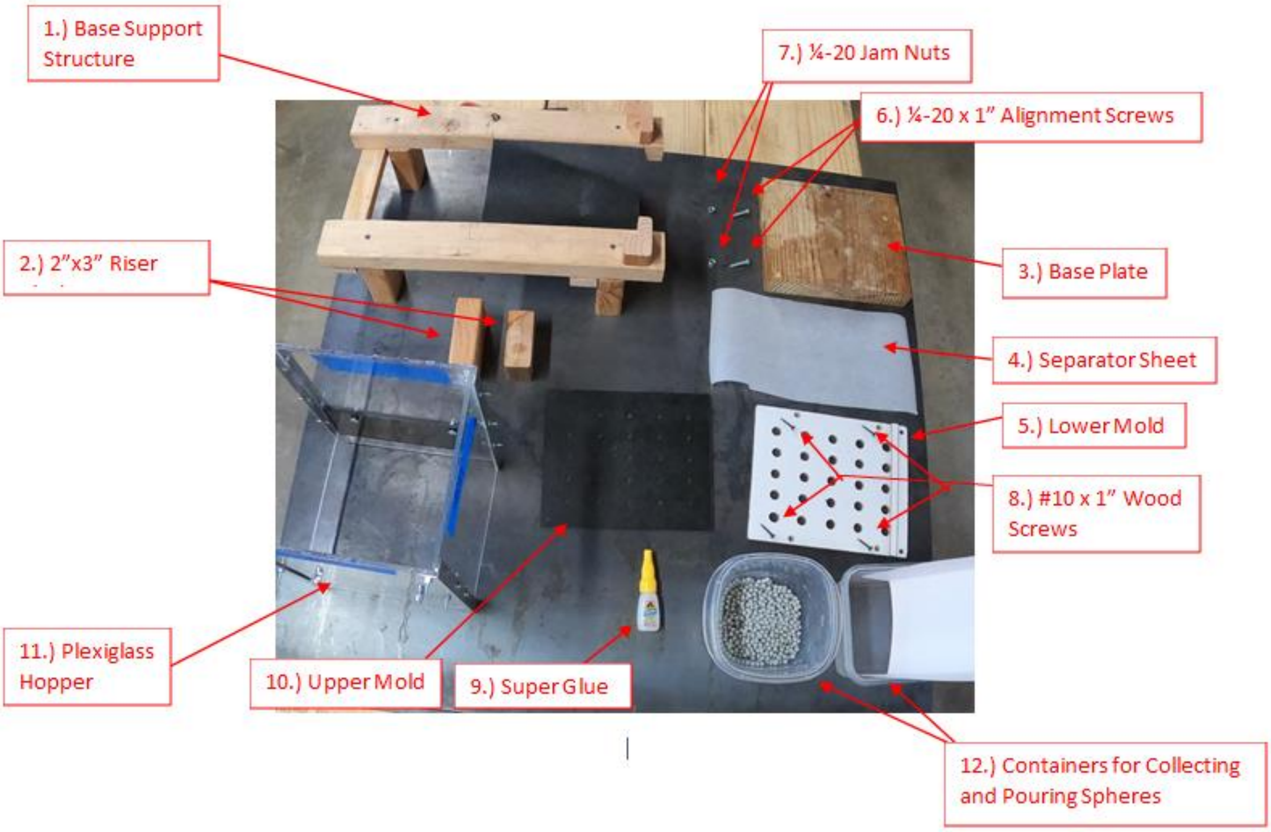


Figure 37: Captioned Breakdown of Working Prototype Assembly

The wooden base plate is shown in more detail in figure 4 below. The pockets drilled into the upper corners prevent any horizontal motion in the alignment screws. The four pilot holes allow for extended use of the retainer screws, which prevent any tilting the alignment screws.

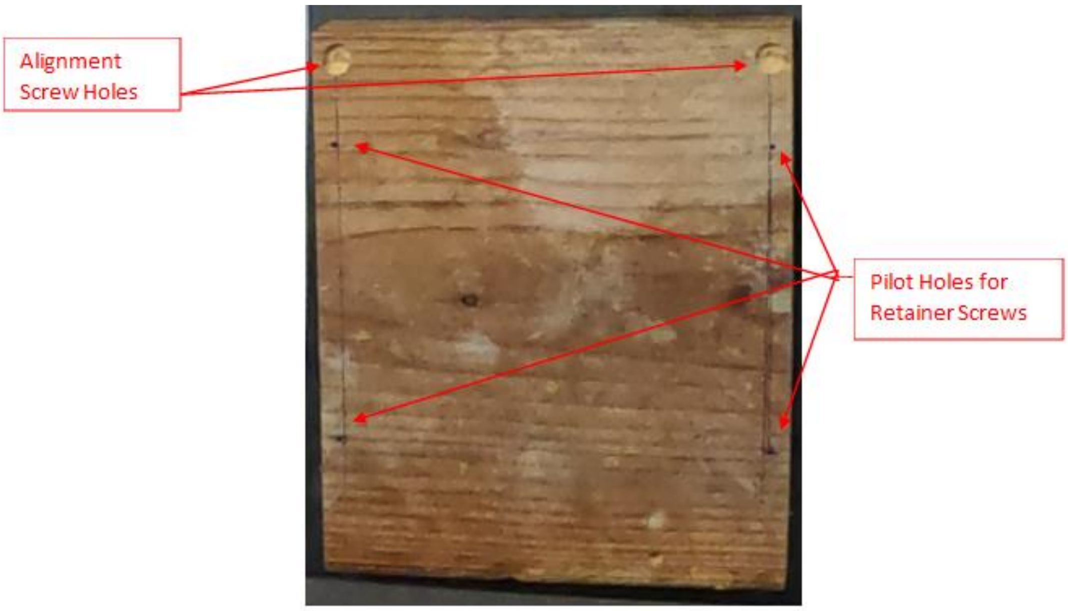


Figure 38: Working Prototype Wooden Base Plate

The lower mold is detailed in Figure 39 below. The separator shown in the figure is parchment paper, but after further testing, this was changed to PTFE sheet for efficiency. Either material will work for this process, but PTFE has less of a tendency to bond with super glue. The 3/16” spacer serves to fill the gap between the lower mold and the top edge of the front slot of the hopper. The gap is necessary for the upper mold to fit into the hopper but needs to be filled when the upper mold is not present.

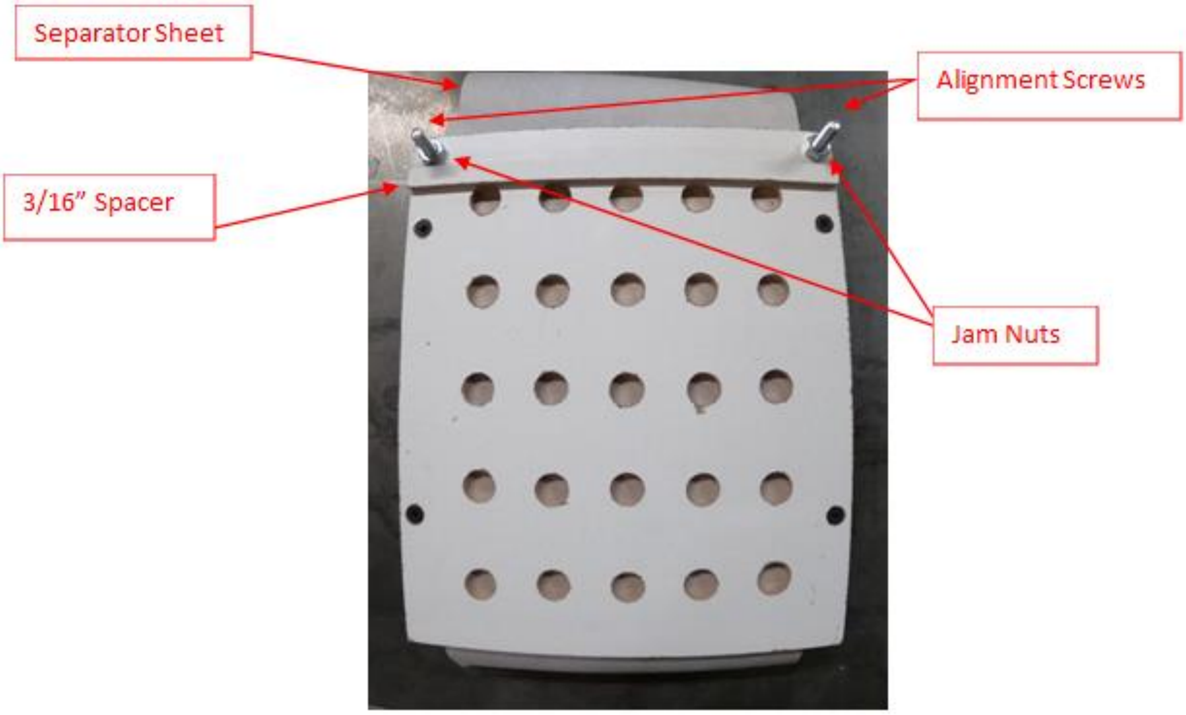


Figure 39: Working Prototype Lower Mold

The Upper mold is detailed in Figures 40 and 41 below. The upper mold is made of 1/16” thick ABS plastic. The gap between the lower and upper mold is shown in Figure 41. This gap ensures that glue from the lower set of spheres does not come in contact with the upper mold.

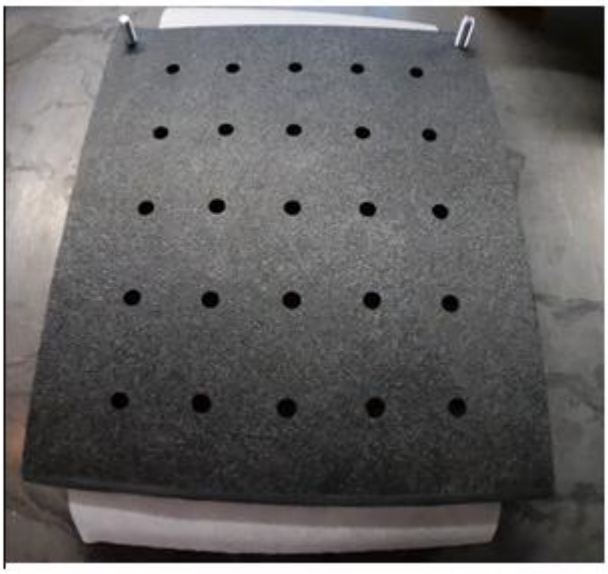


Figure 40: Working Prototype Upper Mold Overhead Detail

Figure 41: Working Prototype Upper Mold Side Detail

Figure 42 details the base support structure. The L-shaped blocks are glued to the upper members and serve to hold the hopper in place while it is tilted to remove excess spheres. The black piece of ABS plastic fits into horizontal slots cut into the support members and serves to guide excess spheres into the overflow reservoir as they fall from the hopper. The upper beams, legs, and lifting blocks are made of 2”x3” pine, and the cross supports are made of 1”x2” pine. All members excluding the L-shaped blocks are fastened together with #10 x 2-1/2” wood screws. It should be noted that the final design uses one longer lifting block rather than the two short ones depicted.

Figure 42: Working Prototype Base Support Structure

The hopper is detailed in Figure 43 below. The side panels are made of 0.22” x 11.75” plexiglass sheets. Its exact dimensions are detailed in the included drawing set. The ¾” aluminum angles are fastened to each corner by a total of 20, #6-32 x ¾” machine screws. The angles offer structural support to the hopper. The 2” x 8” “front window slot” is where the mold assembly is inserted into the hopper. The notches cut into the angles and the slots cut into the side panels were part of a previous design. The plastic pieces on the side panels and the screws that hold them are also part of that design but are used in this design to prevent spheres from falling through the slots in the side panels.

Figure 43: Working Prototype Hopper Overhead View

9 DESIGN DOCUMENTATION

9.1 FINAL DRAWINGS AND DOCUMENTATION

9.1.1 Engineering Drawings

Figures 44 through 64 below are the final detail drawings of every fabricated part used in the final assembly. See Appendix C for the individual SolidWorks part files.

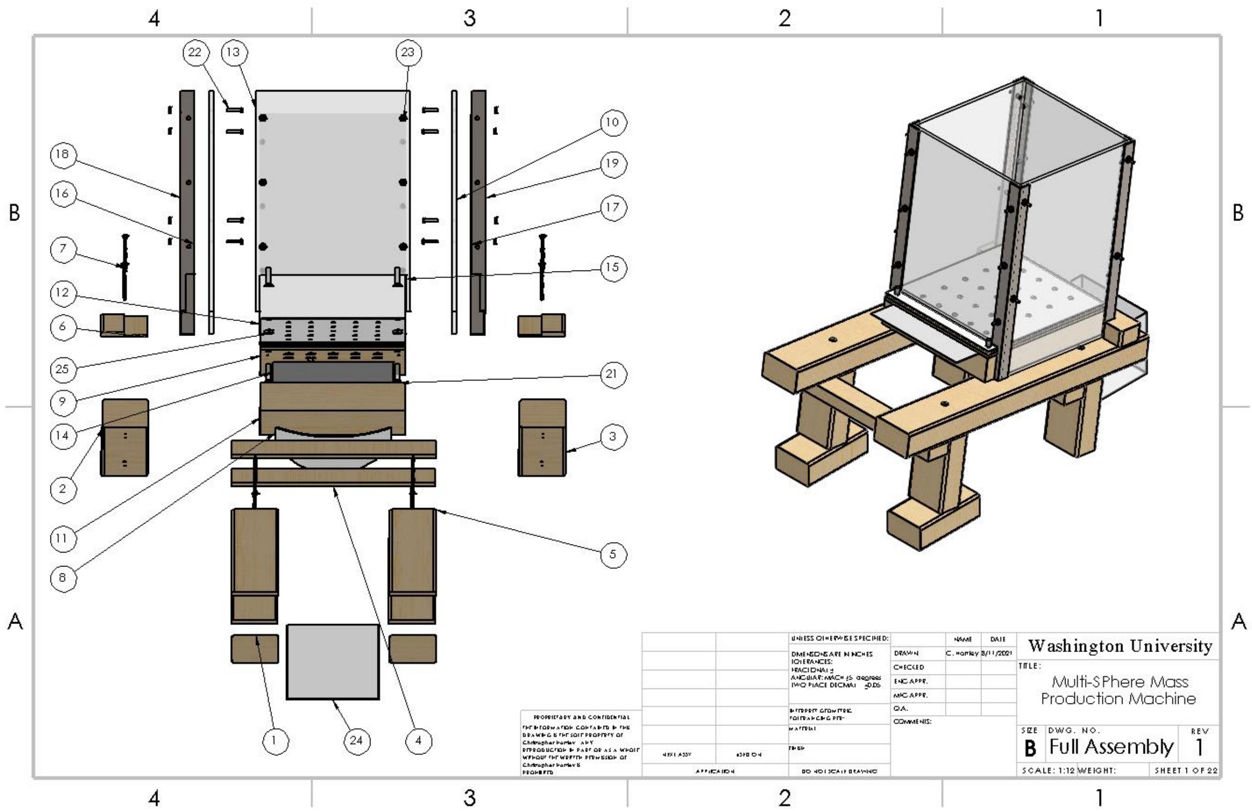


Figure 44: Full Assembly Detail Drawing

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.	Requires Fabrication
1	Base Structure_Riser Blocks_Rev1	Pine 2"x3" Blocks	2	Yes
2	Base Structure_Left Upper Beam_Rev1	Pine 2"x3" Boards	1	Yes
3	Base Structure_Right Upper Beam_Rev1	Pine 2"x3" Boards	1	Yes
4	Base Structure_Cross Support_Rev1	Pine 1"x2" Boards	2	Yes
5	Base Structure_Support Legs_Rev1	Pine 2"x3" Boards	4	Yes
6	Base Structure_Corner Stops_Rev1	Pine 2"x3" Blocks	2	Yes
7	90095A418	#10x2" Screws for Softwood and Plastic-Wood Composites	8	No
8	Base Structure_Guide Plate_Rev1	1/16" Thick ABS Plastic Sheet	1	Yes
9	Lower Mold_Rev1	3/16" Thick Wood with 0.55" Holes	1	Yes
10	Hopper Side Panel_Rev1	0.22" Thick Plexiglass	2	Yes
11	Base Plate_Rev1	2"x10" Pine Board	1	Yes
12	Upper Mold_Rev 1	1/16"" Thick ABS Plastic Sheet with 7 mm Holes	1	Yes
13	Hopper Front Panel_Rev1	0.22" Thick Plexiglass	1	Yes
14	PTFE Sheet	6.5" Wide Strip of PTFE Sheet	1	Yes
15	Hopper Back Panel_Rev1	0.22" Thick Plexiglass	1	Yes
16	Back Left Angle_Rev1	3/4"x1/16" Aluminum Angle	1	Yes
17	Back Angle_Rev1	3/4"x1/16" Aluminum Angle	1	Yes
18	Front Left Angle_Rev1	3/4"x1/16" Aluminum Angle	1	Yes
19	Front Right Angle_Rev1	3/4"x1/16" Aluminum Angle	1	Yes
20	Porcelain Sphere	6 mm Porcelain Spheres	4	No
21	CSBOLT 0.2500-20x1x0.75-S-C	1/4"-20 x 1" Machine Screw	2	No
22	CR-PHMS 0.138-32x0.75x0.75-C	#6-32 x 3/4" Machine Screw	20	No
23	90480A007	#6-32 Low-Strength Steel Hex Nut	20	No
24	Overflow Container	5"x5"x4" Tuppleware Container	1	No
25	94846A029	1/4"-20 Medium-Strength Steel Thin Hex Nut	2	No

Washington University

TITLE:

Multi-SPhere Mass Production Machine

SIZE B DWG. NO. Bill of Materials REV 1

SCALE: 1:12 WEIGHT: SHEET 2 OF 22

Figure 45: Engineering Drawing Bill of Materials

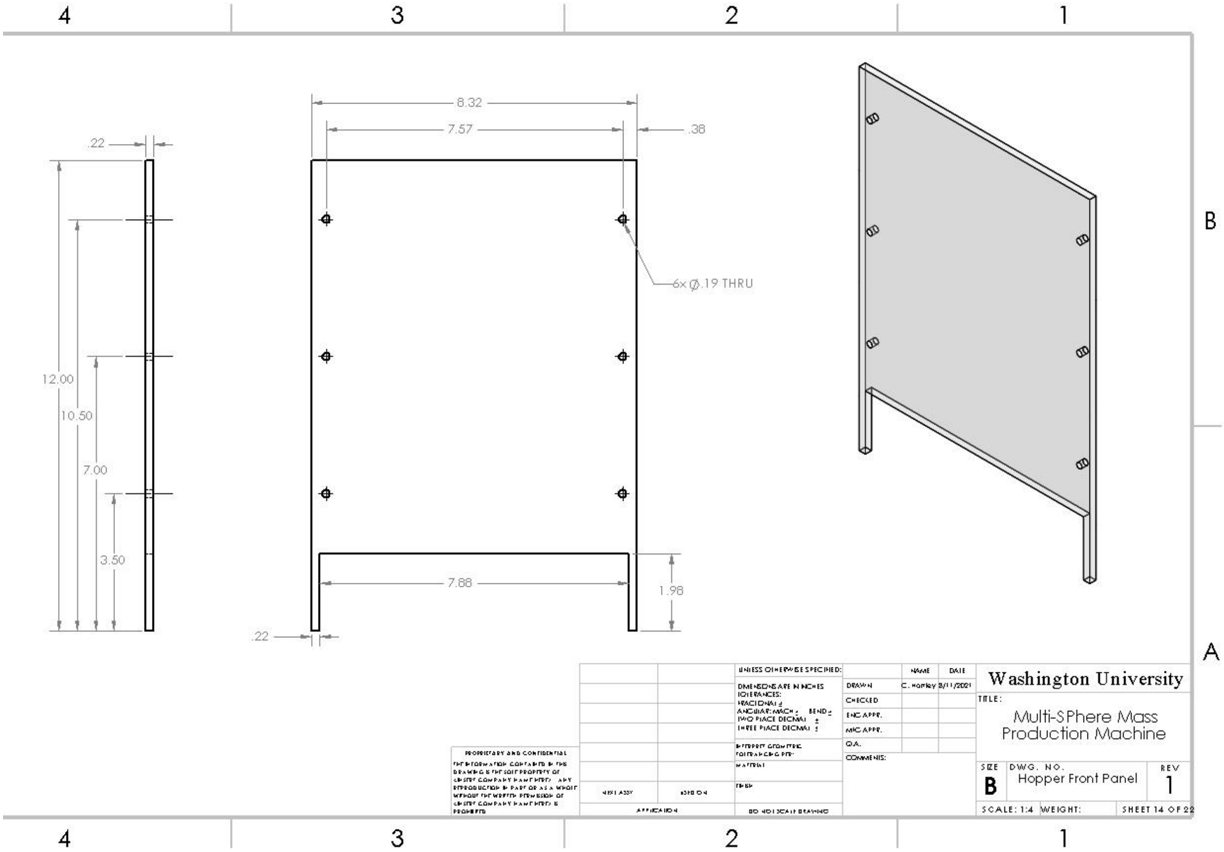


Figure 46: Engineering Drawing Hopper Front Panel

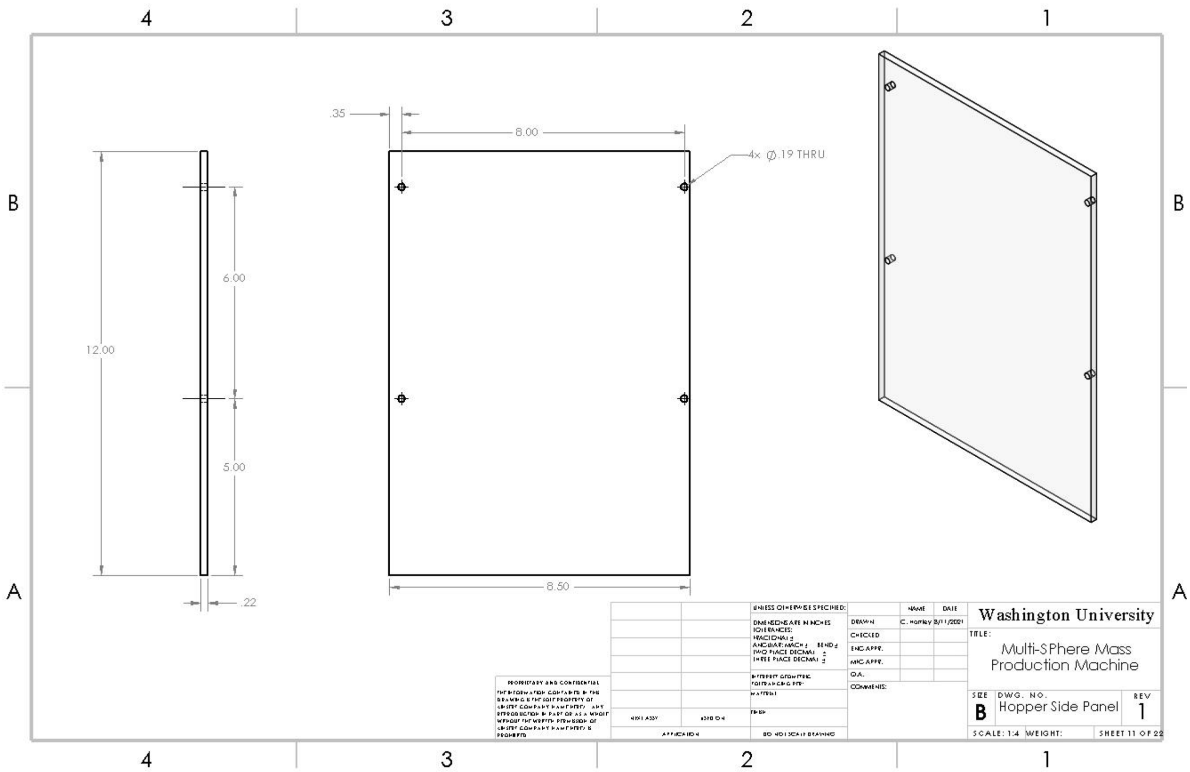


Figure 47: Engineering Drawing Hopper Side Panel

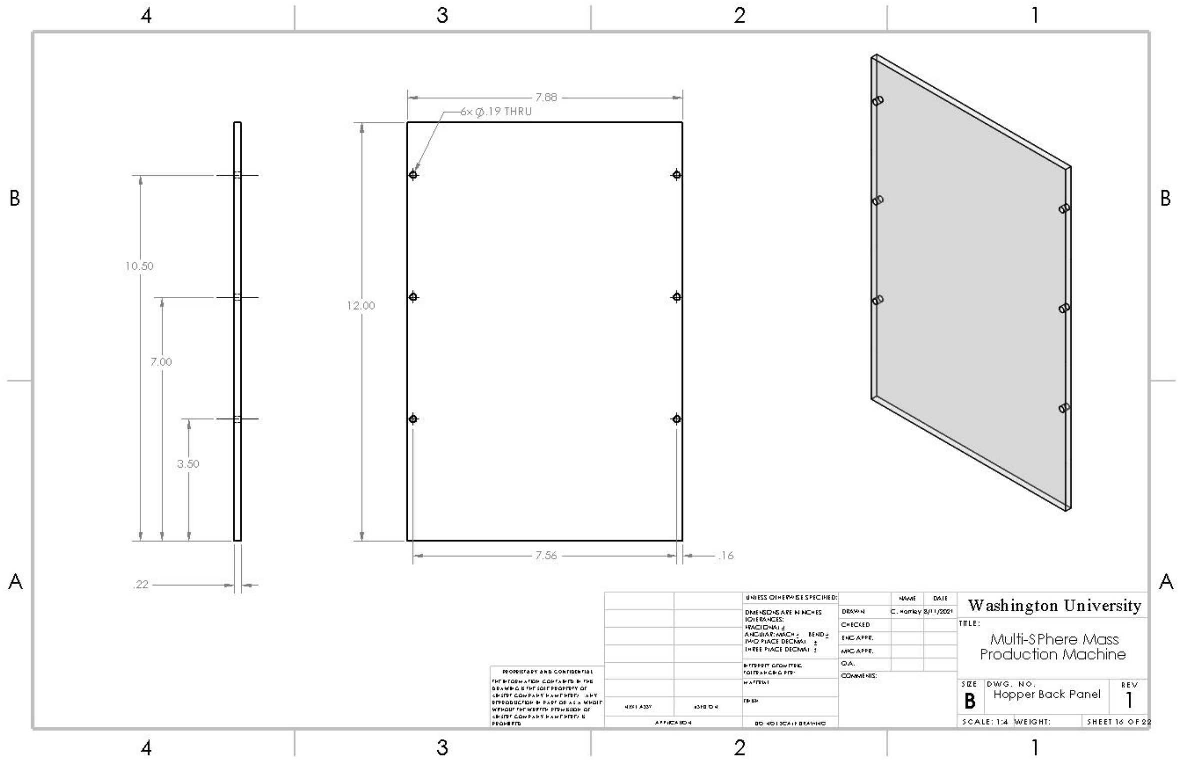


Figure 48: Engineering Drawing Hopper Back Panel

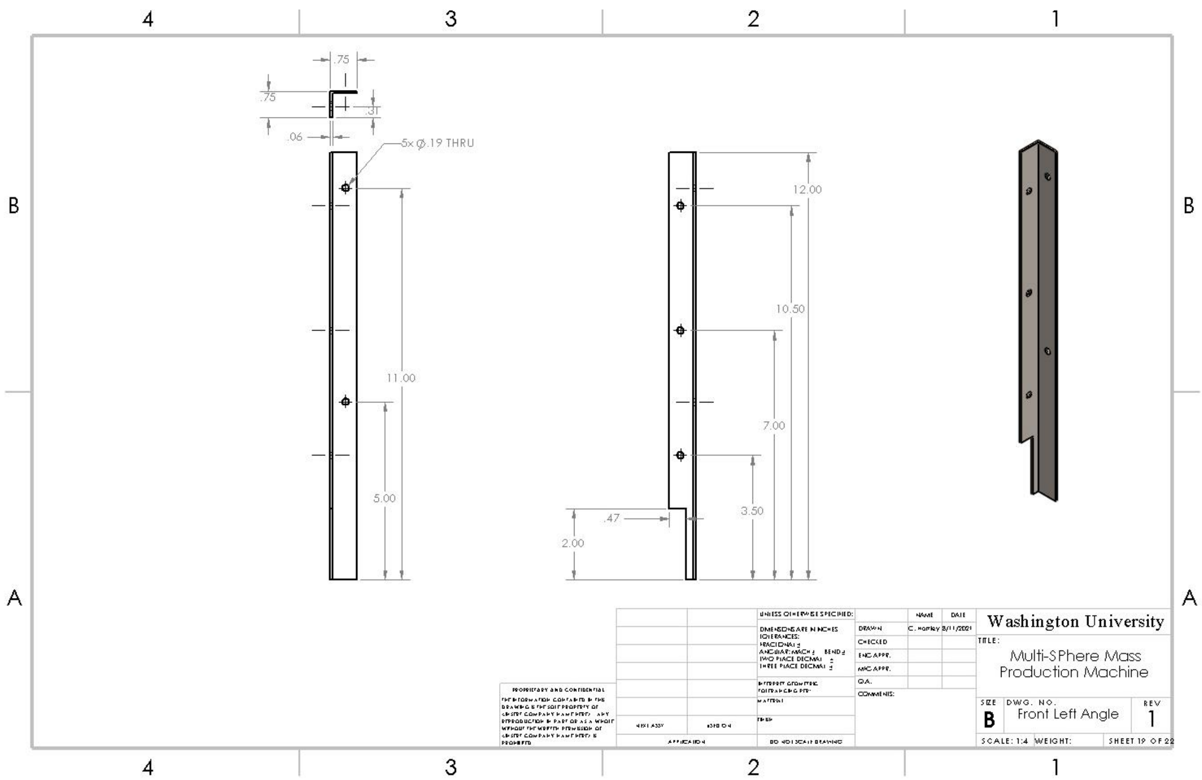


Figure 49: Engineering Drawing Hopper Join Front Left Angle

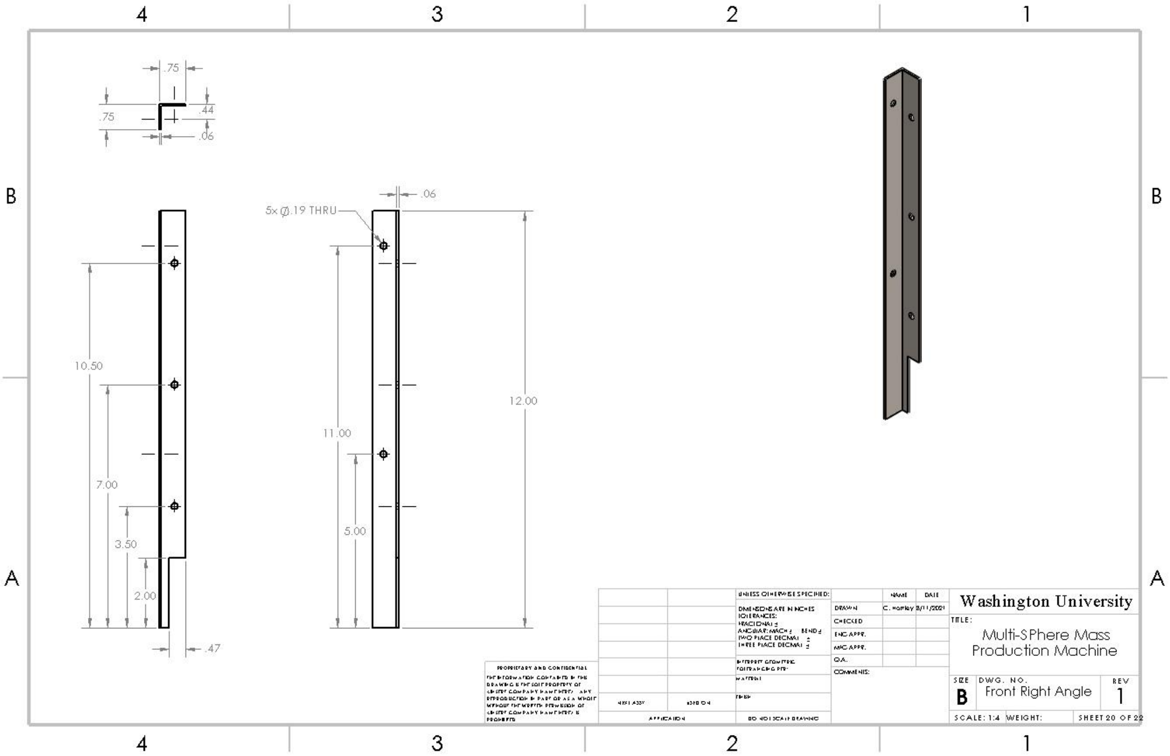


Figure 50: Engineering Drawing Hopper Join Front Right Angle

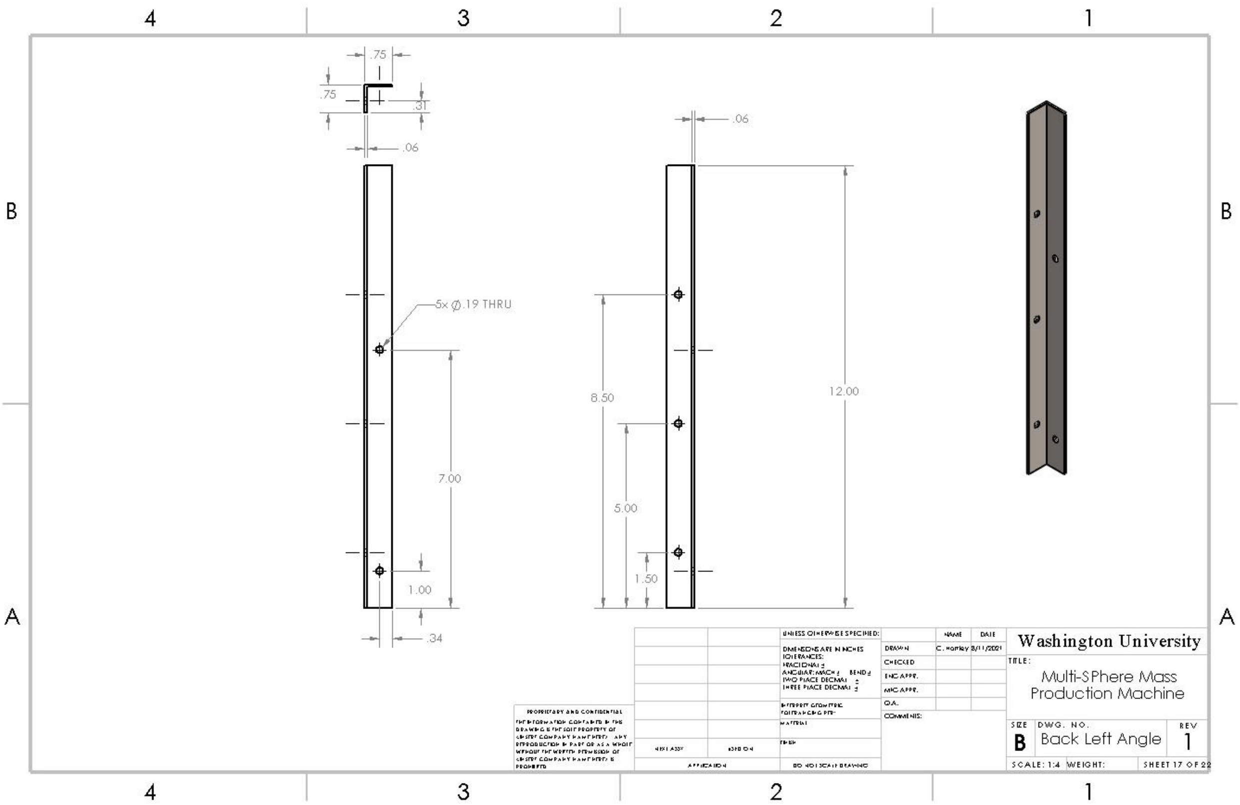


Figure 51: Engineering Drawing Hopper Join Back Left Angle

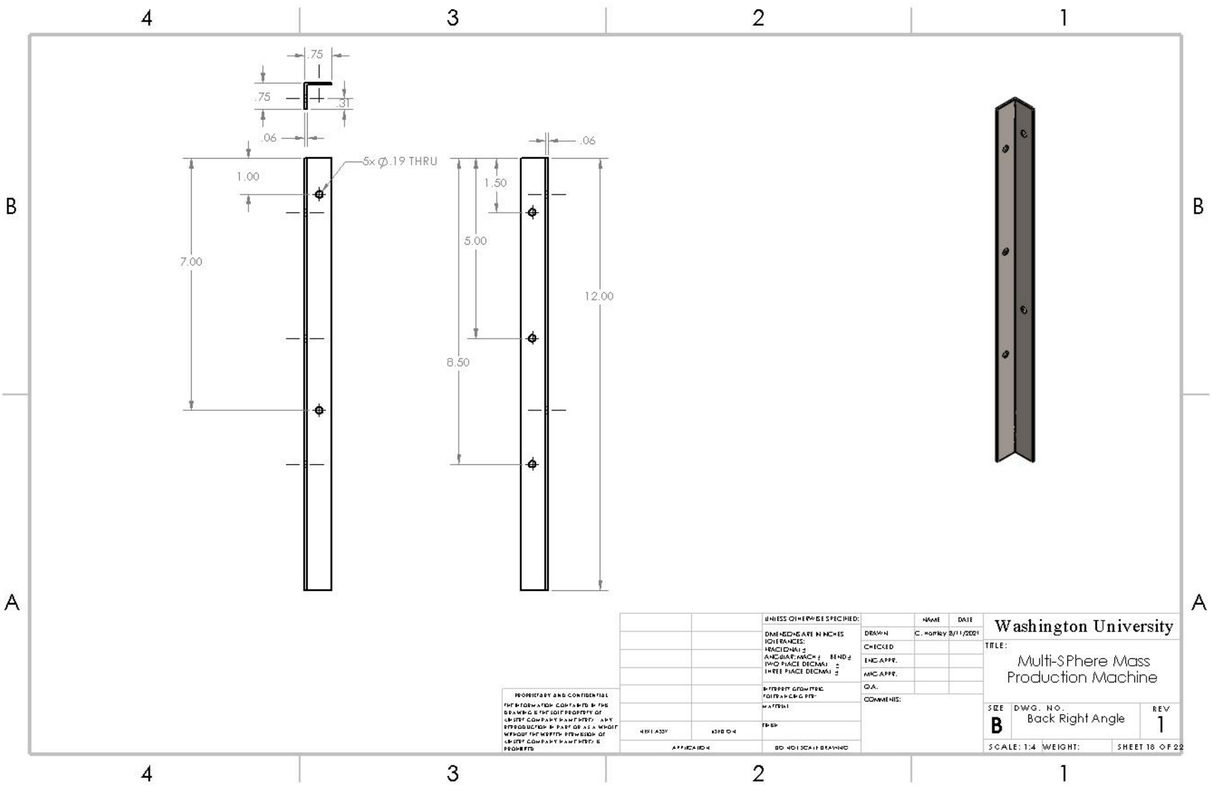


Figure 52: Engineering Drawing Hopper Join Back Right Angle

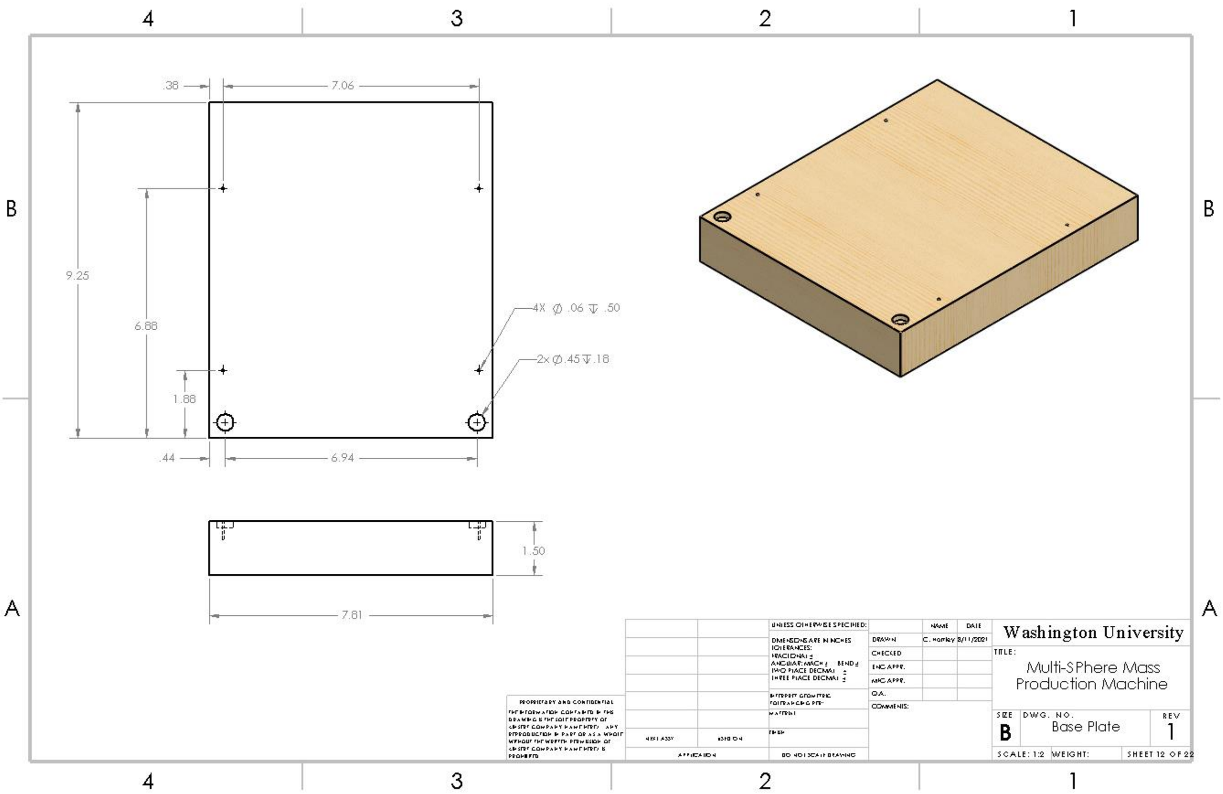


Figure 53: Engineering Drawing Base Plate

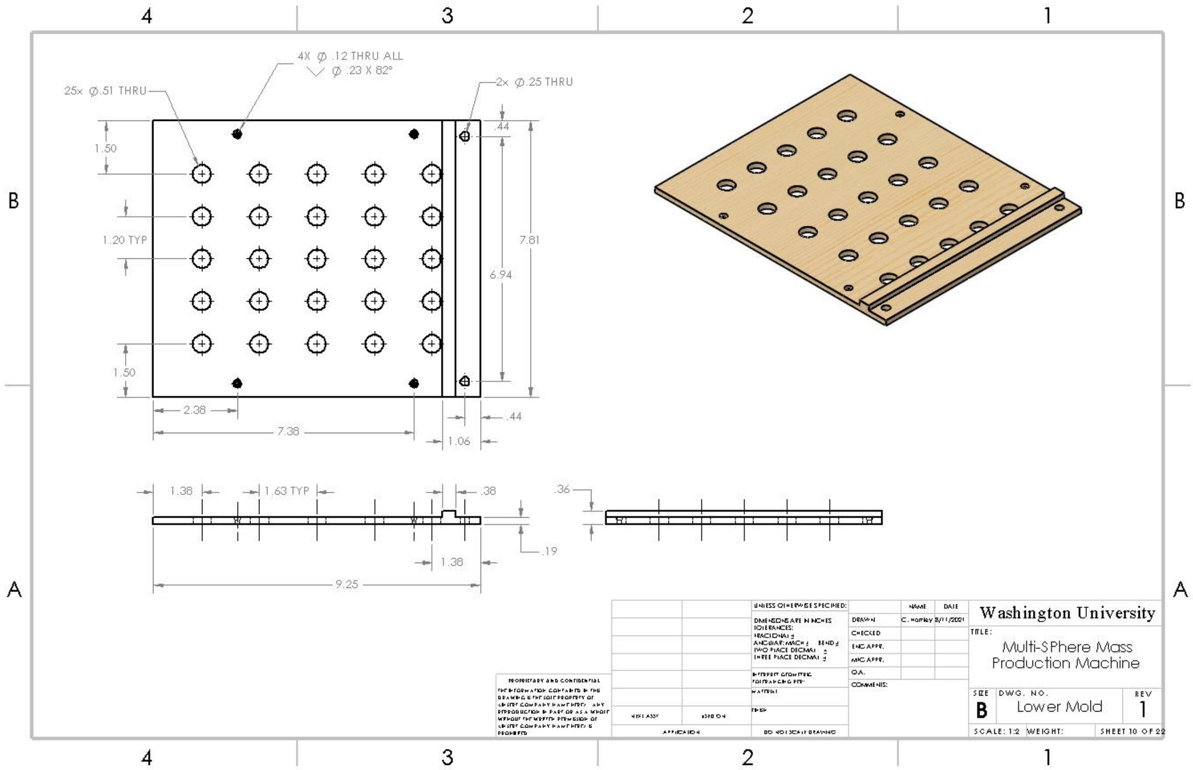


Figure 54: Engineering Drawing Lower Mold

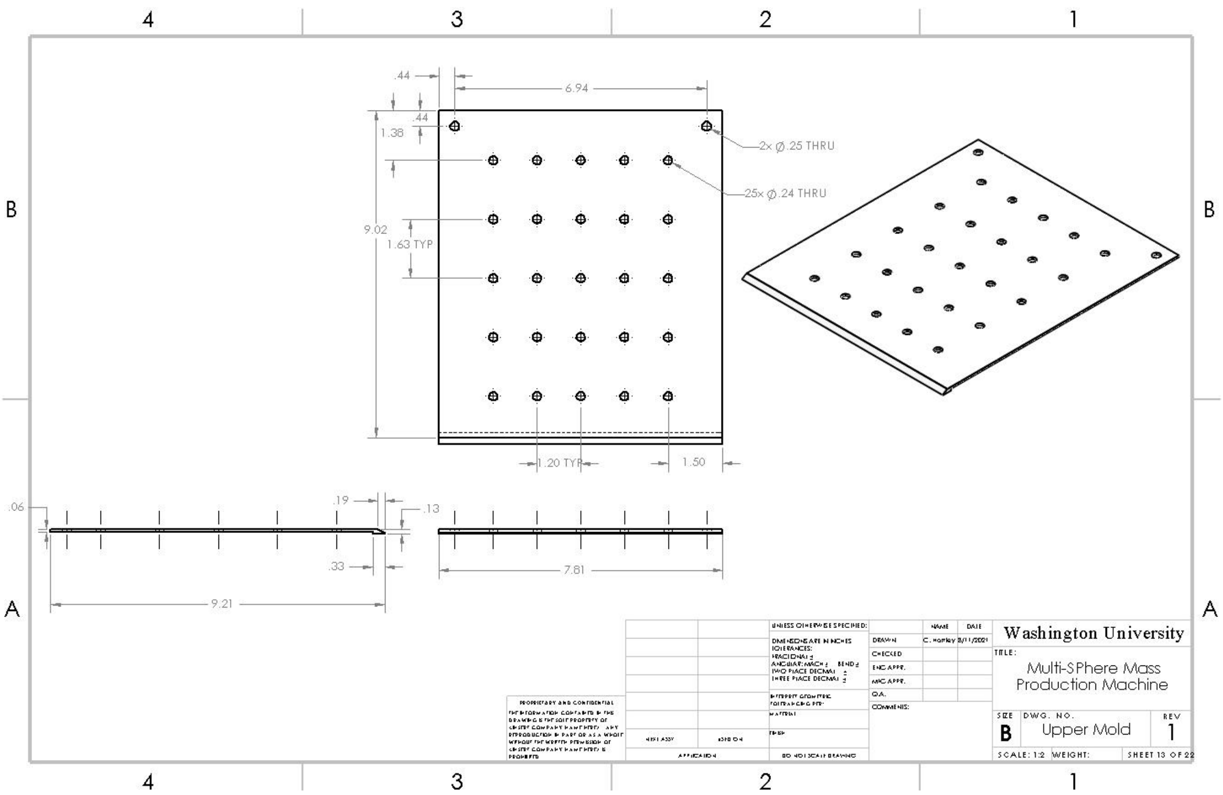


Figure 55: Engineering Drawing Upper Mold

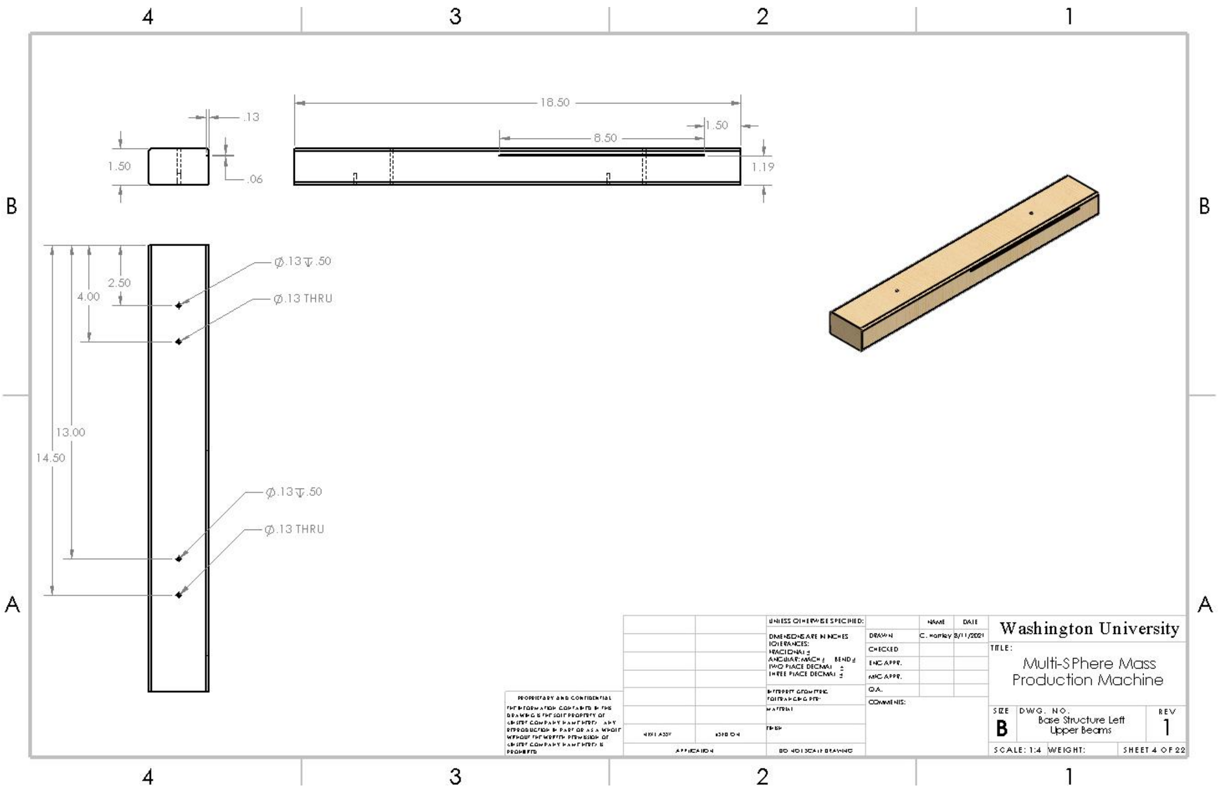


Figure 56: Engineering Drawing Base Structure Left Upper Beam

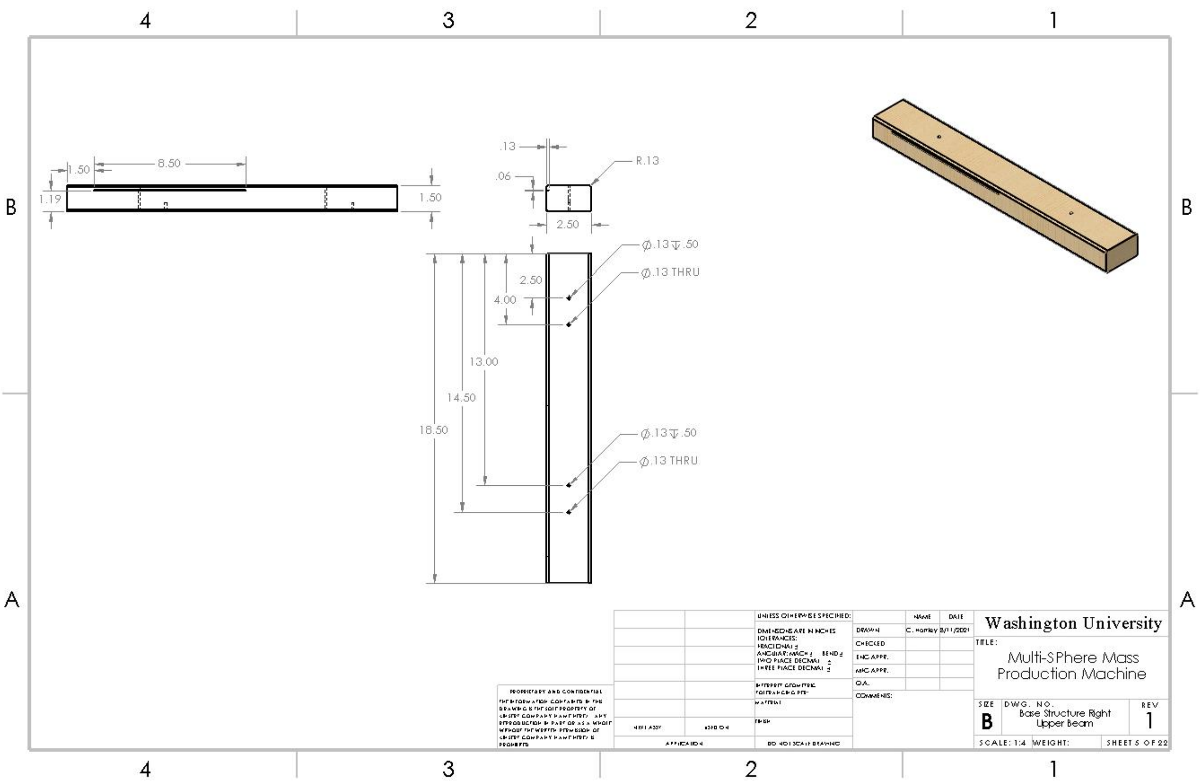


Figure 57: Engineering Drawing Base Structure Right Upper Beam

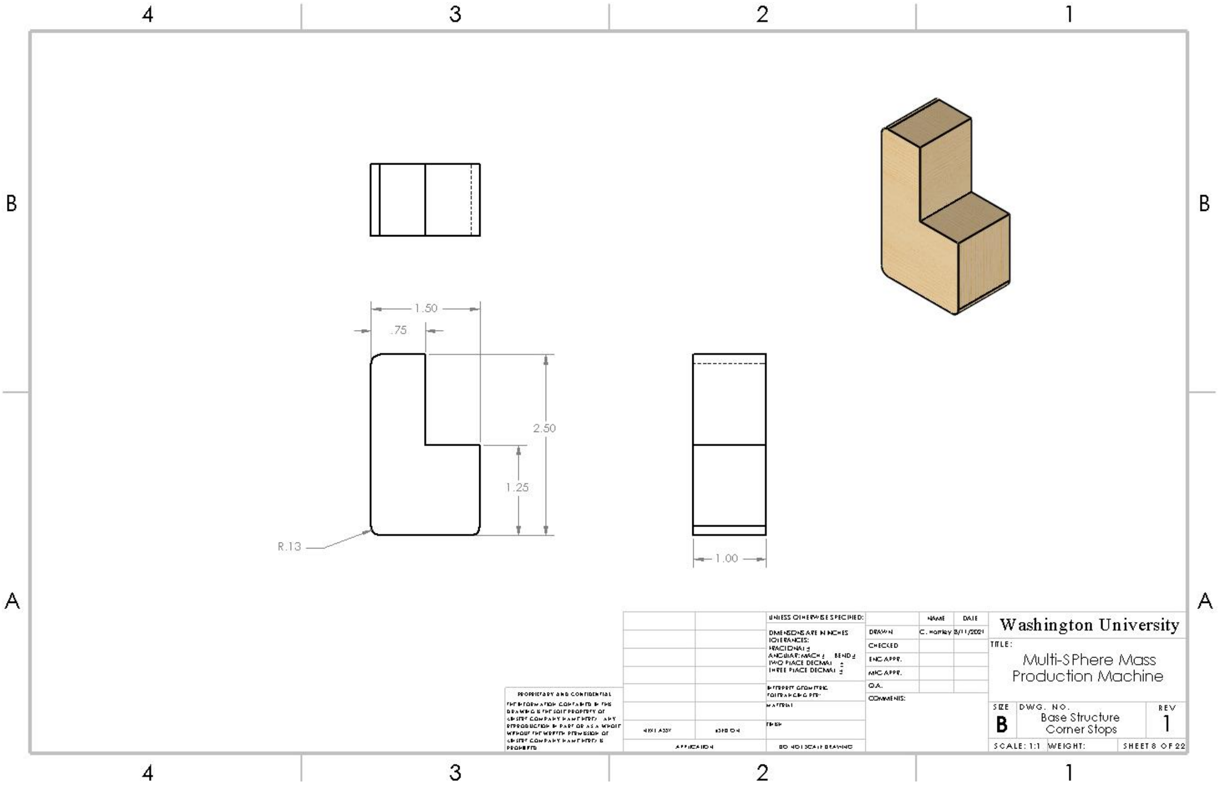


Figure 58: Engineering Drawing Base Structure Corner Stops

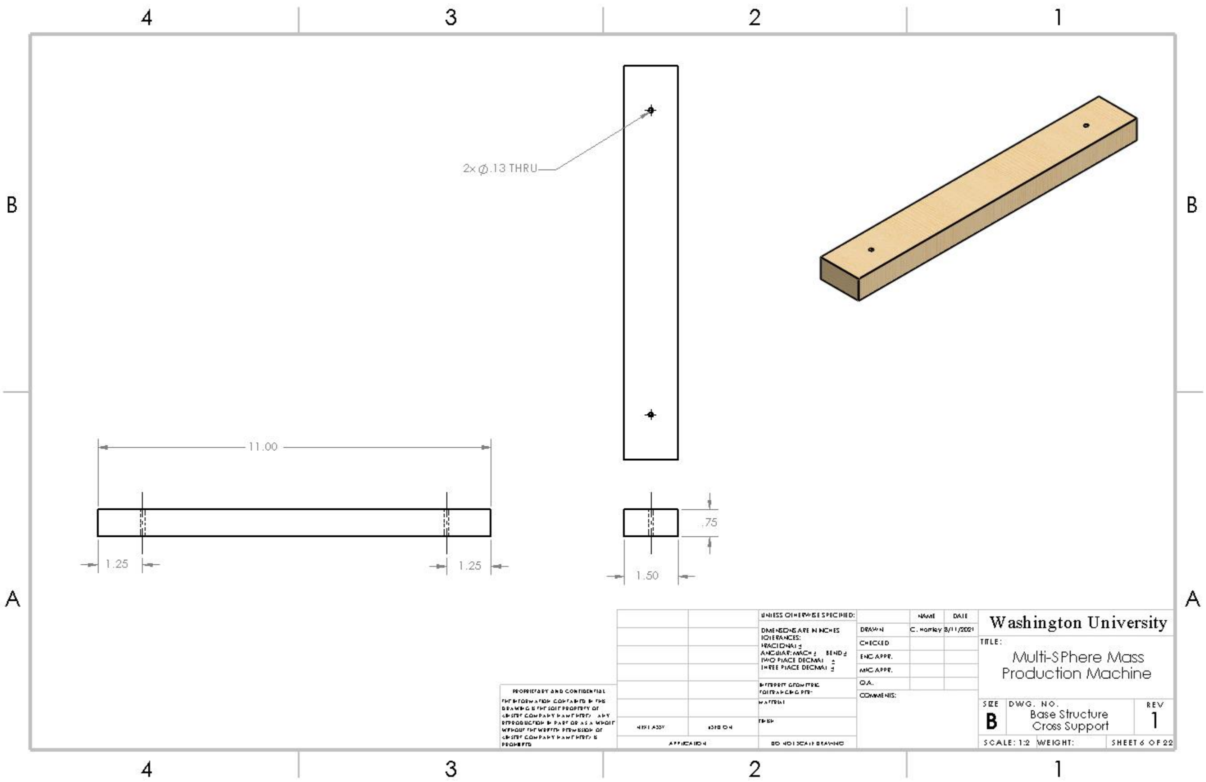


Figure 59: Engineering Drawing Base Structure Cross Support

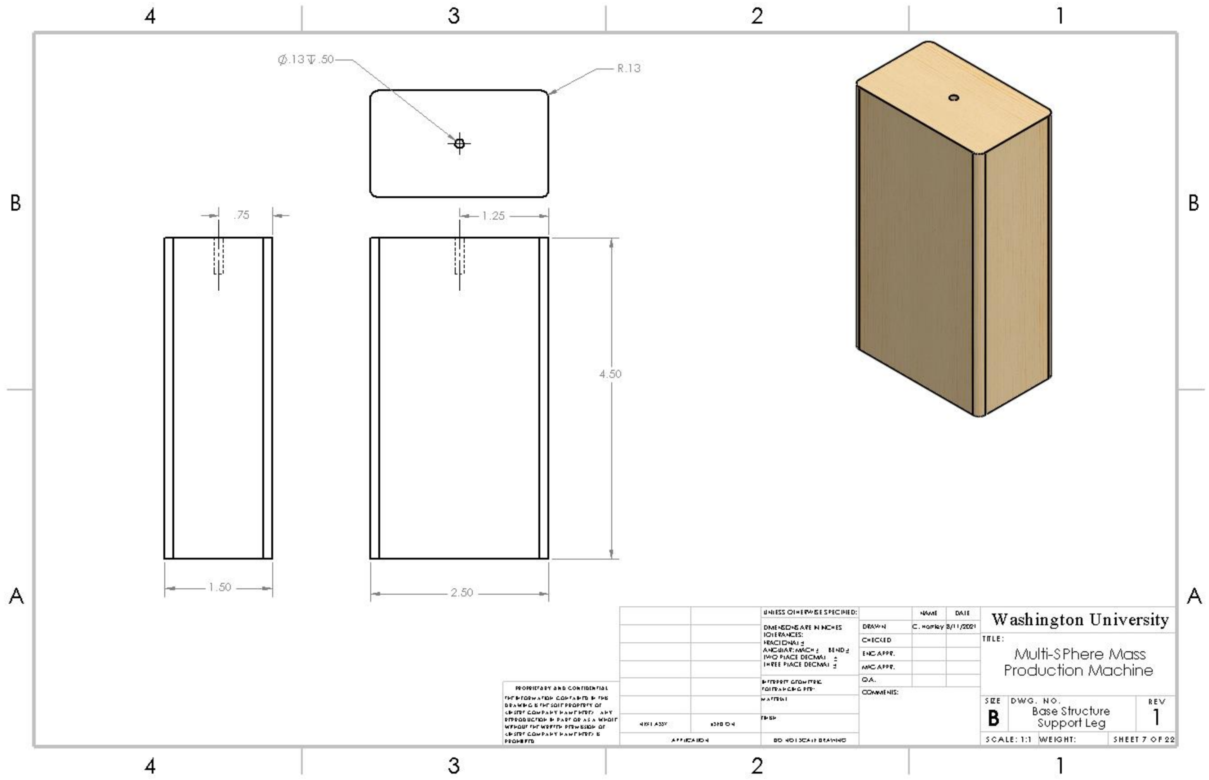


Figure 60: Engineering Drawing Base Structure Support Leg

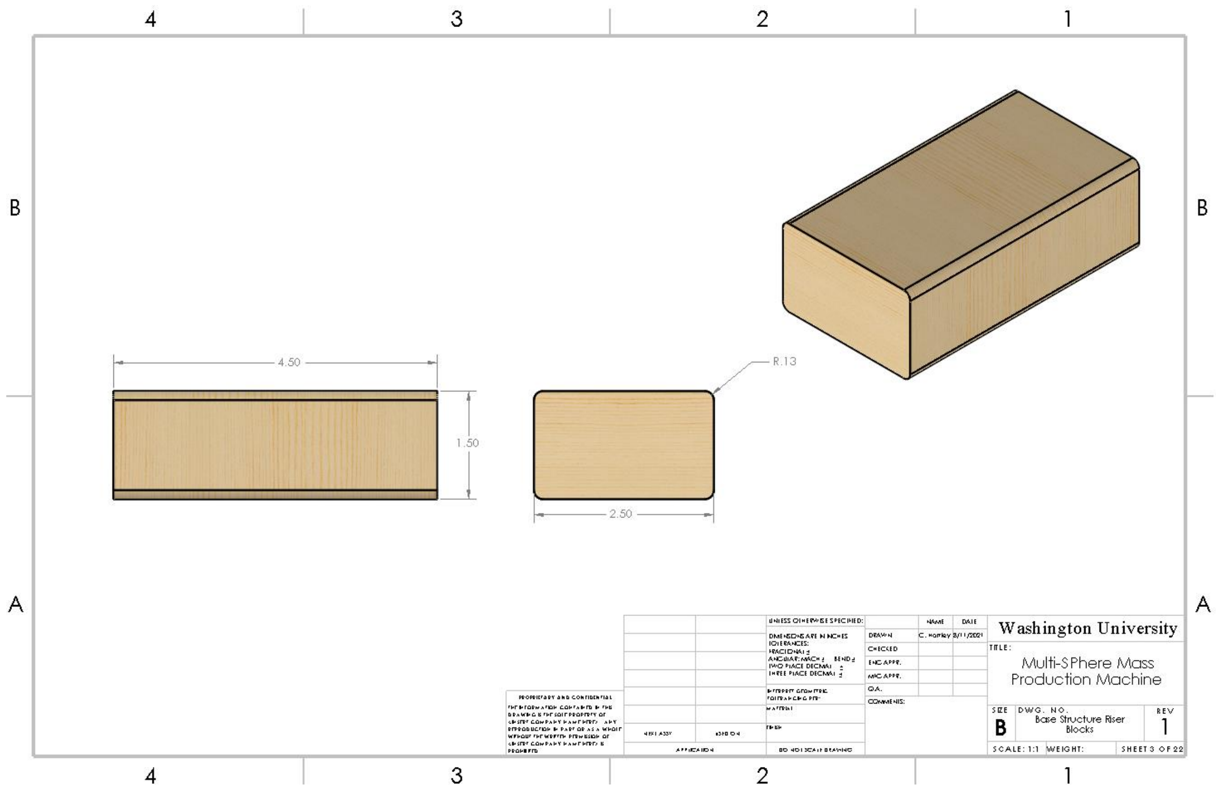


Figure 61: Engineering Drawing Base Structure Riser Blocks

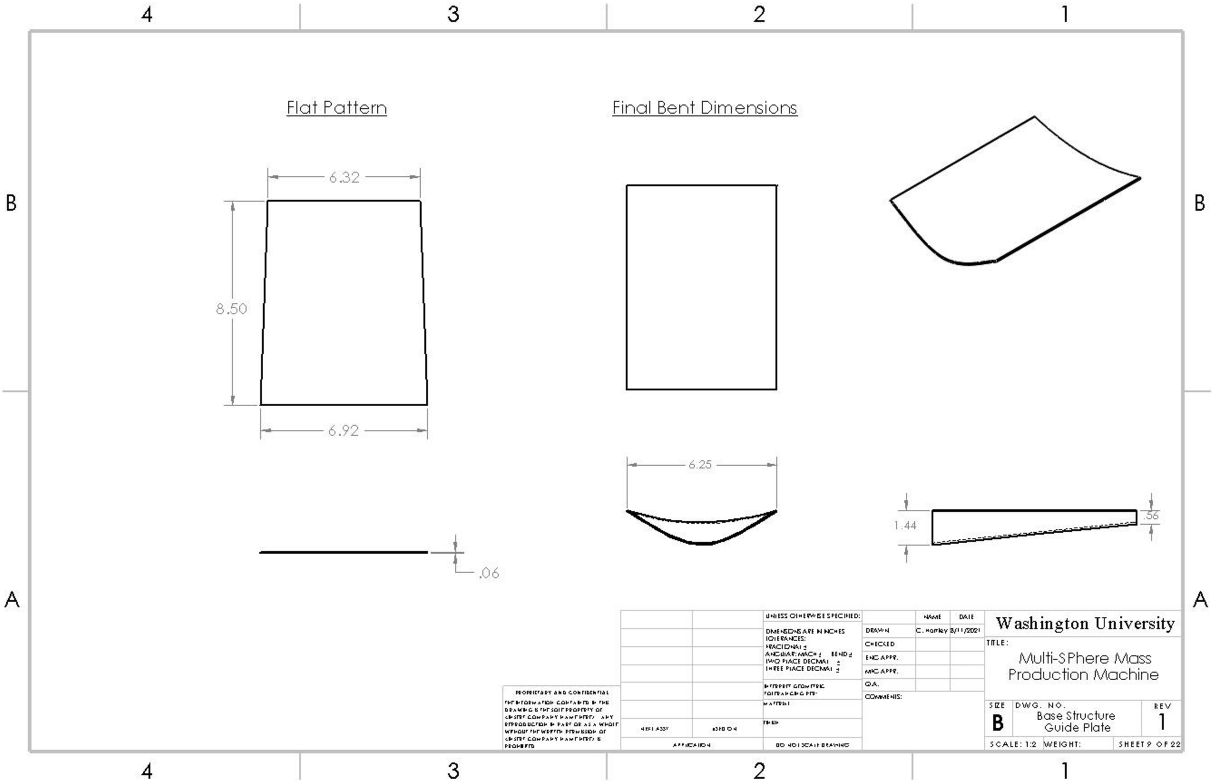


Figure 62: Engineering Drawing Base Structure Guide Plate

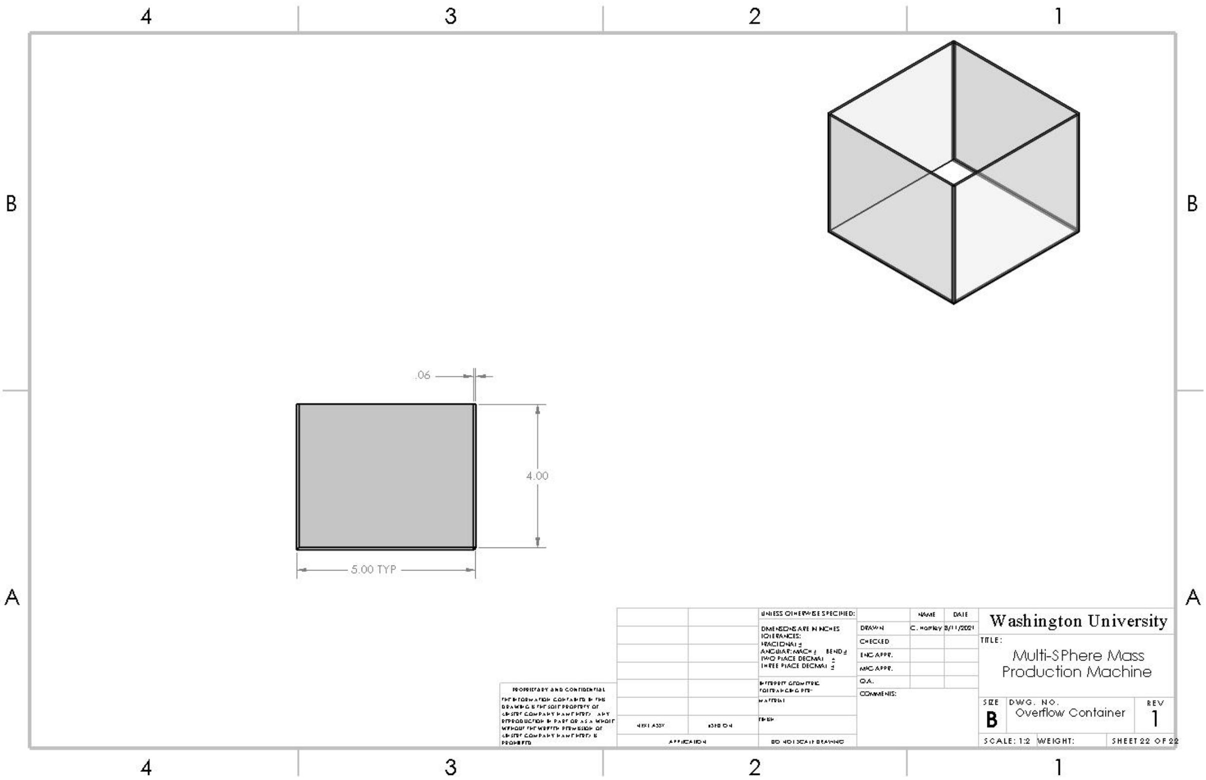


Figure 63: Engineering Drawing Overflow Container

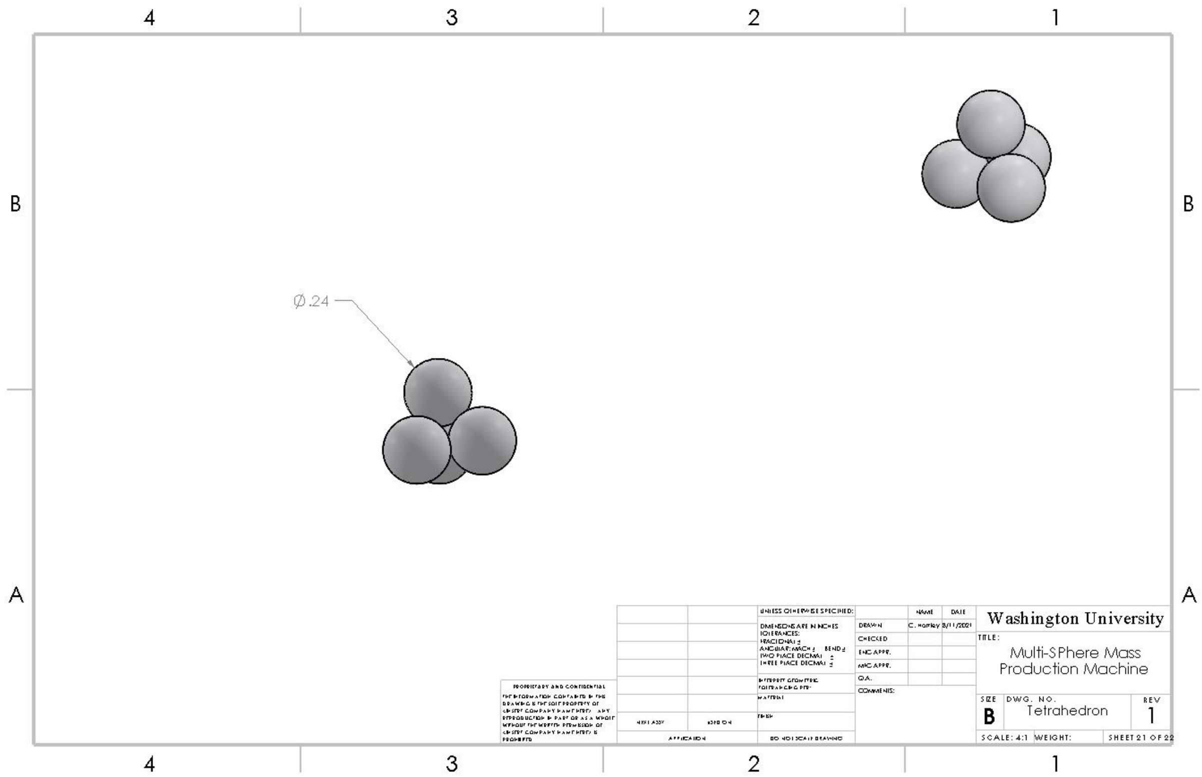


Figure 64: Engineering Drawing Finalized Tetrahedron Structure

9.1.2 Sourcing Instructions

Table 9: Material Sourcing Table

Item Number	Part Number	Description	Catalog Number	Unit Cost ($)	Web Link	Qty	Total Cost of Material Used ($)	Total Cost Required ($)
1	Base Plate	2x10 board cut to 8" long for Base Plate.	NA	$9.84	bairdbrothers.com	1	$9.84	$9.84
2	Plexiglass Sheet	24"x4"x0.22" Clear Acrylic Sheet cut into four pieces for Hopper Walls.	7453	$31.04	onlinemetals.com	1	$31.04	$31.04
3	MDF Board	3/16"x24"x48" MDF Board cut to size for Lower Mold.	313382855	$5.33	homedepot.com	1	$0.30	$5.33
4	Porcelain Sphere	6mm Porcelain Spheres for Final Tetrahedral Parts.	293646027884	$25.22	ebay.com	1	$25.22	$25.22
5	ABS Plastic Plate	12" x 12" x 1/16" thick ABS plastic sheet cut to size and bent for overflow guide plate.	B0049MWXM8	$5.53	amazon.com	1	$5.53	$5.53
6	Alignment Screws	1/4"-20 x 1" machine screws.	91099A479	$0.30	mcmaster.com	2	$0.60	$7.44
7	1" Wood Screws	#8 x 1" flat head wood screws for mounting lower mold to base plate.	300513591	$0.02	homedepot.com	4	$0.07	$16.70

Item Number	Part Number	Description	Catalog Number	Unit Cost ($)	Web Link	Qty	Total Cost of Material Used ($)	Total Cost Required ($)
8	2" Wood Screws	#10 x 2" flat head wood screws for assembling the wooden base structure.	90252A242	$0.20	mcmaster.com	8	$1.60	$10.00
9	Base Structure 2"x3"	2" x 3" x 96" board cut to length for upper beams, feet, riser blocks, and corner stops for wooden base support structure.	312570697	$3.25	homedepot.com	1	$2.25	$3.25
10	Base Structure 1"x2"	1" x 2" x 96" board cut to length for 11" long cross supports for wooden base support structure.	306896195	$2.87	homedepot.com	1	$2.87	$2.87
11	PTFE Sheet	16"x20" PTFE sheet cut to 6.5" x 9" fastened beneath lower mold to prevent glue from bonding to base plate.	700401159368	$6.88	amazon.com	1	$2.29	$6.88
12	Super Glue	Super glue used to bond spheres into final shape.	7805001	$4.35	amazon.com	2	$8.70	$8.70
						Total Cost:	**$90.30**	**$132.80**

9.2 FINAL PRESENTATION

Follow the link below for a presentation video giving a high-level overview of this design project:

https://youtu.be/g22KiG8zTuM

10 TEARDOWN

11 APPENDIX A - PARTS LIST

This is an initial list of parts for the cost of raw materials, components, assemblies etc.

Table A- 1: Initial Parts List

Item Number	Part Number	Description	Catalog Number	Unit Cost ($)	Web Link	Qty	Total Cost ($)
1	Base Plate	2x10 board cut to 8" long for Base Plate	NA	$9.84	bairdbrothers.com	1	$9.84
2	Plexiglass Sheet	24"x4"x0.22" Clear Acrylic Sheet for Hopper Walls	7453	$31.04	onlinemetals.com	1	$31.04
6	MDF Board	3/16"x24"x48" MDF Board for Upper and Lower Molds	313382855	$5.33	homedepot.com	1	$5.33
7	Porcelain Sphere	6mm Porcelain Spheres	293646027884	$25.22	ebay.com	1	$25.22
8	PTFE Plate	1/16"x12"x24" PTFE sheet for upper and lower separator plates	9266K22	$64.58	mcmaster.com	1	$64.58
10	Alignment Dowel Pin	1/4" dowel rod for alignment dowel pins	203360194	$1.07	homedepot.com	1	$1.07

Item Number	Part Number	Description	Catalog Number	Unit Cost ($)	Web Link	Qty	Total Cost ($)
11	Set Screw	1/4"-20x 1/2" set screws for clamping wax paper between lower mold and base plate	171684	$0.49	fastenal.com	4	$1.96
12	Parchment Paper	Non-stick parchment paper used to separate parts from lower mold and prevent sticking to base plate	8347585	$2.67	walmart.com	1	$2.67
13	Super Glue	Super glue used to bond spheres into final shape	7805001	$4.35	amazon.com	1	$4.35
						Total Cost:	$146.06

12 APPENDIX B - BILL OF MATERIALS

This is the final list of parts for the cost of raw materials, components, assemblies etc. which states the actual bill of your final project.

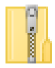
Table B- 1: Final Parts List

Item Number	Part Number	Description	Catalog Number	Unit Cost ($)	Web Link	Qty	Total Cost of Material Used ($)	Total Cost Required ($)
1	Base Plate	2x10 board cut to 8" long for Base Plate.	NA	$9.84	bairdbrothers.com	1	$9.84	$9.84
2	Plexiglass Sheet	24"x4"x0.22" Clear Acrylic Sheet cut into four pieces for Hopper Walls.	7453	$31.04	onlinemetals.com	1	$31.04	$31.04
3	MDF Board	3/16"x24"x48" MDF Board cut to size for Lower Mold.	313382855	$5.33	homedepot.com	1	$0.30	$5.33
4	Porcelain Sphere	6mm Porcelain Spheres for Final Tetrahedral Parts.	293646027884	$25.22	ebay.com	1	$25.22	$25.22
5	ABS Plastic Plate	12" x 12" x 1/16" thick ABS plastic sheet cut to size and bent for overflow guide plate.	B0049MWXM8	$5.53	amazon.com	1	$5.53	$5.53
6	Alignment Screws	1/4"-20 x 1" machine screws.	91099A479	$0.30	mcmaster.com	2	$0.60	$7.44
7	1" Wood Screws	#8 x 1" flat head wood screws for mounting lower mold to base plate.	300513591	$0.02	homedepot.com	4	$0.07	$16.70
8	2" Wood Screws	#10 x 2" flat head wood screws for assembling the wooden base structure.	90252A242	$0.20	mcmaster.com	8	$1.60	$10.00
9	Base Structure 2"x3"	2" x 3" x 96" board cut to length for upper beams, feet, riser blocks, and corner stops for wooden base support structure.	312570697	$3.25	homedepot.com	1	$2.25	$3.25

Item Number	Part Number	Description	Catalog Number	Unit Cost ($)	Web Link	Qty	Total Cost ($)	Item Number
10	Base Structure 1"x2"	1" x 2" x 96" board cut to length for 11" long cross supports for wooden base support structure.	306896195	$2.87	homedepot.com	1	$2.87	$2.87
11	PTFE Sheet	16"x20" PTFE sheet cut to 6.5" x 9" fastened beneath lower mold to prevent glue from bonding to base plate.	700401159368	$6.88	amazon.com	1	$2.29	$6.88
12	Super Glue	Super glue used to bond spheres into final shape.	7805001	$4.35	amazon.com	2	$8.70	$8.70
						Total Cost:	**$90.30**	**$132.80**

13 APPENDIX C – COMPLETE LIST OF ENGINEERING DRAWINGS

Below is a .zip file containing all solid part files and assembly files for the design developed for this project.



Multi-Sphere Mass Production Solid Parts.zip

14 ANNOTATED BIBLIOGRAPHY

[1] Connor, Stephen T, et al. *Sinterable Metal Paste for Use in Additive Manufacturing*. 2 Oct. 2018.

The patent filed by Connor et al for a "sinterable metal paste" gives insight to a possible material that could be used to form the constituent spheres that make up the physical approximated parts. However, the added processing required to produce the spheres before beginning the process of combining the spheres into their final tetrahedral structures makes this material less than an ideal choice.

[2] W., Suma, and Michelle M. "Original Buckyballs Magnets - the Best Magnetic Stress Balls Magnets Color Nickle." *BuckyballsCube*, 5 Mar. 2020, www.buckyballscube.com/buckyball-magnets/62-2-original-buckyballs-magnets.html#/1-color-nickle.

Magnetic spheres are a simple and easily attainable way to create tetrahedrons. This specific product has been proven to be a simple way to sinter spheres into a more complex shape. Unfortunately, the final parts would tend to bond with each other, which is a critical constraint of this project.

[3] Caruso, Eric. "1-1/2' X 9-1/2' POPLAR LUMBER 2x10." *2x10 (1-1/2" x 9-1/2") Poplar S4S Lumber, Boards, & Flat Stock from Baird Brothers*, www.bairdbrothers.com/1-12-x-9-12-Poplar-Lumber-2x10-P3814.aspx.

Baird Brothers is a simple way to purchase finished wood cut to custom lengths, avoiding purchasing excess material that may not be used. This was utilized in this project for the 2"x10" block that makes up the body of the "base plate", which holds the molds in place.

[4] “0.22’ Acrylic Sheet Clear -PART #: 7453.” *Order 0.22" Plastic Sheet Acrylic Clear Online, Thickness: 7/32"*, www.onlinemetals.com/en/buy/plastic/0-22-acrylic-sheet-clear/pid/7453?variant=7453_12_24&utm_source=google&utm_medium=organic&utm_campaign=surfaces-across-google&utm_term=7453_12_24.

Online Metals provides reasonable pricing for a range on materials, including plastics. Onlinemetals.com was used to source the clear acrylic sheet used to construct the hopper side panels for this project.

[5] “3/16 In. 2 Ft. x 4 Ft. Black CHALK / White Marker Mdf Board-00066.” *The Home Depot*, www.homedepot.com/p/3-16-in-2-ft-x-4-ft-Black-Chalk-White-Marker-MDF-Board-00066/313382855.

Home Depot was used to source many of the products used in this design. The "lower mold" was made of 3/16" thick MDF board with a chalk board finish on one side and a dry erase finish on the other side. This specific product was chosen only for its price and not based on the finish.

[6] “1 Lbs. 6 MM Fast Cutting Grey ABRASIVE Sphere Ceramic PORCELAIN Tumbling MEDIA 744633331437.” *eBay*, www.ebay.com/itm/293646027884?_trkparms=aid%3D1110006%26algo%3DHOMESPLICE.SIM%26ao%3D1%26asc%3D233036%26meid%3D4a6e3daddad44ab99c091298dc13c227%26pid%3D101195%26rk%3D2%26rkt%3D12%26sd%3D293646027892%26itm%3D293646027884%26pmt%3D1%26noa%3D0%26pg%3D2047675%26algv%3DSimplAMLv8MlcUltbPairwiseNativeDarwoXgbV1&_trksid=p2047675.c101195.m1851&amdata=cksum%3A2936460278844a6e3daddad44ab99c091298dc13c227%7Cenc%3AAQAGAAACAKVfkP3egRkbqP2tixE032kxr0GXlhDa2m7FF7rn3FopGc9IfZlKJJfT24qoW2ZIE%252BnoSAPxBvEW4%252FsrVOwo58X0cWvIGNZfUx%252BxF3u04WgytSyulOdQBmvjL88Lc4SGoqsafz6svYEWHtzZ%252B444gLmX5zaRtBBPjLzo7yFMVi3KJr5UmZOrXH1bJzKSz1Zn3i8OxZ9EBi08L9gQnE2Ka9w%252B1umdb%252FNiPSqWRBf60mkFk43%252BfPZTw%252FnDuR5HmooXZrjOIS8eazXcuxCwuyYqIhwPS1qejBT9DGUKmzpN%252BSmgZcxYnTRfDXKPWr02Ck9pI8AFDz3qVnkKbUKdwuB1S6cc5cbWxabQ5VqtGs2Za2p26IrJ0%252FUh3FLi3nQhKkuFSxi3puAz9dljwshDHVaCsJ8yoXXYfHb%252FWQTQ0h7TDTCJdWkaXPyLGTAi6UAPznVs9mMqfpCKwcxOG4%252FQiJg0gBc%252BgCOpOtzFmFwn9Fc0mmC4OUJv1TCL0Zg9BEkZ%252BzwAmPb%252Bxa3pr3OqAOHhlMxgKqFrjcwIetf1ESA3kOO86ASLRf%252F%252FqyYKGWtpqMmG54OSUc1GAkSki%252FAZgt%252FOZix5G2%252BrqJz9zcot3oJeS%252FlhZ4cPp9p7SlsUwo%252Fl5YAKan531qWVWKnieGOp6ZYyL3lQNiyY0Pr57KQHMEexd7rUoay8%7Campid%3APL_CLK%7Cclp%3A2047675&epid=2002782390.

The porcelain spheres used for the final produced product were purchased from ebay.com. The spheres are originally intended and marketed to be used as a polishing/tumbling media.

[7] “Oversized Chemical-Resistant Slippery PTFE Sheet.” *McMaster*, www.mcmaster.com/9266K22/.

A 1/16" thick sheet of PTFE was specified for use as the "upper mold" in the original design and was sourced from McMaster-Carr. While the product has excellent non-stick properties, the high price justified a material change for the upper mold in the final design.

[8] “1/4 In. x 48 IN. Raw Wood ROUND DOWEL-HDDH1448.” *The Home Depot*, www.homedepot.com/p/1-4-in-x-48-in-Raw-Wood-Round-Dowel-HDDH1448/203360194.

The original fixture design utilizes wooden dowels for alignment between the base plate and both molds. The dowel pins were sourced from Home Depot. The wooden pins were eliminated in the final design.

[9] “1/4’-20 X 1/2’ Hex DRIVE Flat Point Grade 18-8 Stainless Steel Socket Set Screw: Fastenal.” *Fastenal Company*, www.fastenal.com/products/details/0171684.

The original design utilized 1/4"-20 set screws to fasten the lower mold to the base plate. This Fastenal product provides alignment without interfering with the upper mold. The set screws would remain flush with the surface of the lower mold without the need to countersink the holes. These were ultimately replaced in the final design with a cheaper product that offers more clamping force, is cheaper, and does not require the mounting holes to be threaded.

[10] “Great Value 50 Sq Ft Non-Stick Parchment Paper.” *Walmart.com*, 17 June 2021, www.walmart.com/ip/Great-Value-50-sq-ft-Non-Stick-Parchment-Paper/713110340?wmlspartner=wlpa&selectedSellerId=0&wl13=1177&&adid=22222222227000000000&wl0=&wl1=g&wl2=c&wl3=42423897272&wl4=pla-51320962143&wl5=9022814&wl6=&wl7=&wl8=&wl9=pla&wl10=8175035&wl11=local&wl12=713110340&veh=sem&gclid=Cj0KCQjw_8mHBhClARIsABfFgphMaJfyJVJ78HX6-4eXfw8cjaeV-ogI-sdnEXHNcRlf8Hp4sy0MPoQaAuAcEALw_wcB&gclsrc=aw.ds.

The original mold design included Walmart brand parchment paper between the lower mold and the base plate to prevent parts from sticking to the base plate, thus extending its life. Walmart provides a reasonable price for this product.

[11] “Gorilla Super Glue, 15 Gram, Clear, (Pack of 1).” *Amazon*, Gorilla Company, 16 Jan. 2007, www.amazon.com/Gorilla-Super-Glue-Gram-Clear/dp/B001IY82FM.

Gorilla Super Glue is the quickest setting, strongest, cheapest glue that was found available on the market. With a set time of ten second, this product was ideal for the applications of this product.

[12] John. “Ten Most Common Type of Rocks You Can Find in Rivers.” *How to Find Rocks*, Amazon Services LLC, 31 July 2021, howtofindrocks.com/what-rocks-are-found-in-rivers/.

This geology blog provides useful information on the kinds of rocks most commonly found in rivers. This information was used to determine the range of physical properties that the final product must fall within.

[13] “Density of Selected Solids.” *Engineering ToolBox*, 2009, www.engineeringtoolbox.com/density-solids-d_1265.html.

Engineering Toolbox is a well-known source for engineering and scientific information and education. This website was used in this product to determine the physical properties of various materials in order to create a bounding range of properties for the final product produced in this project. The physical properties used included density and elastic modulus.

[14] “ISO/ASTM 52901:2017.” *ISO*, 20 July 2017, www.iso.org/standard/67288.html.

This standard identifies OSHA Safety and Occupational Health requirements for machine guarding in industrial environments. This document sets all safety requirements for any tooling required to produce products in a machine shop environment. This was the accepted condition under which it was assumed work would take place for this project. Adherence to this standard was a primary safety requirement for prototype construction during this project.

[15] “United States Department of Labor.” *1910.212 - General Requirements for All Machines. | Occupational Safety and Health Administration*, 13 Mar. 2001, www.osha.gov/laws-regs/regulations/standardnumber/1910/1910.212.

This standard identifies OSHA Safety and Occupational Health requirements for machine guarding in industrial environments. This document sets all safety requirements for any tooling required to produce products in a machine shop environment.

[16] “United States Department of Labor.” *1926.57 - Ventilation. | Occupational Safety and Health Administration*, Occupational Safety and Health Administration, 15 May 2002, www.osha.gov/laws-regs/regulations/standardnumber/1926/1926.57.

This standard identifies OSHA Safety and Occupational Health requirements for general and specific ventilation and exhaust requirements to maintain air quality within the guidelines set forth in OSHA Standard 1926.55(a) - Exposure Limits for Gasses, Vapors, Fumes, Dusts, and Mists. This is the driver for our methods of sintering/combining elements for Additive Manufacturing, as well as construction of prototype forms.

[17] “ISO - 83.180 - Adhesives.” *ISO.org*, 7 Aug. 2021, www.iso.org/ics/83.180/x/.

This ISO contains testing standards for general adhesives between various materials as well as establishes requirements and accepted methods for preparing adhesive surfaces prior to bonding. Adherence to the standards set forth under this ISO ensure uniformity of prepared surfaces for adhesion and potential sintering (and un-sintering) standards. This ISO also allows us to utilize accepted standards for verifying bond strength and adhesion performance.